Experimental Capabilities for Applied Nuclear Science at RPI

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DOE Nuclear Data Needs and Capabilities for Applications (NDNCA) workshop, LBNL, May 27-29, 2015

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This work was supported by the following DOE grants: ***KAPL/BMPC/NCSP POs 103971, 7013680, DE-NAOOO1814, DE-FG03-03NA00079, DE-FG52-06NA26202, DE-FG52-09NA29453****.*

Overview

- The Gaerttner LINAC Center at RPI
- Capability Matrix
- Measurement Capabilities and Examples
  - **Thermal Region:** Transmission, Capture, Fission, (S(α,β) at SNS)
  - **Resolved Resonance Region**: Transmission, Capture, Fission
  - **Unresolved Resonance Region**: Transmission, Capture
  - **Fast Neutrons**: Transmission, Scattering, Prompt Fission Neutron Spectrum
  - **Lead Slowing Down Spectrometer**: Fission, (n, alpha), (n, p), Capture
  - **Prompt fission neutrons**: The gamma tagging method

The target room

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Why Should We Care About Nuclear Data?

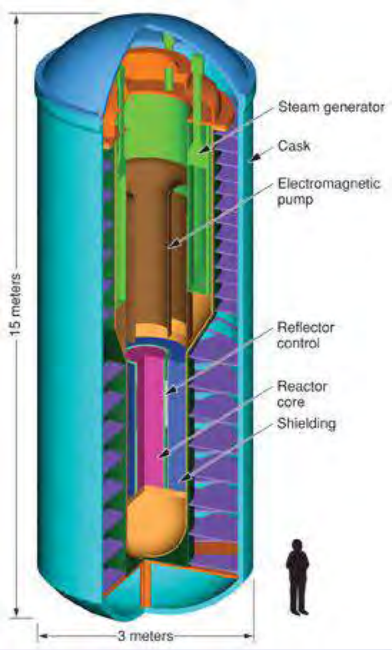
Reactor Physics Calculations

Nuclear Data (Uncertainty)

Geometry Data

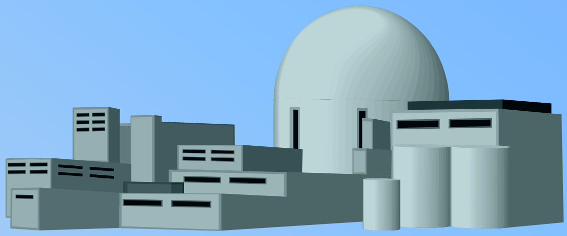
Computational Methods (Physics) (Uncertainty??)

Results Accuracy??



www.llnl.gov

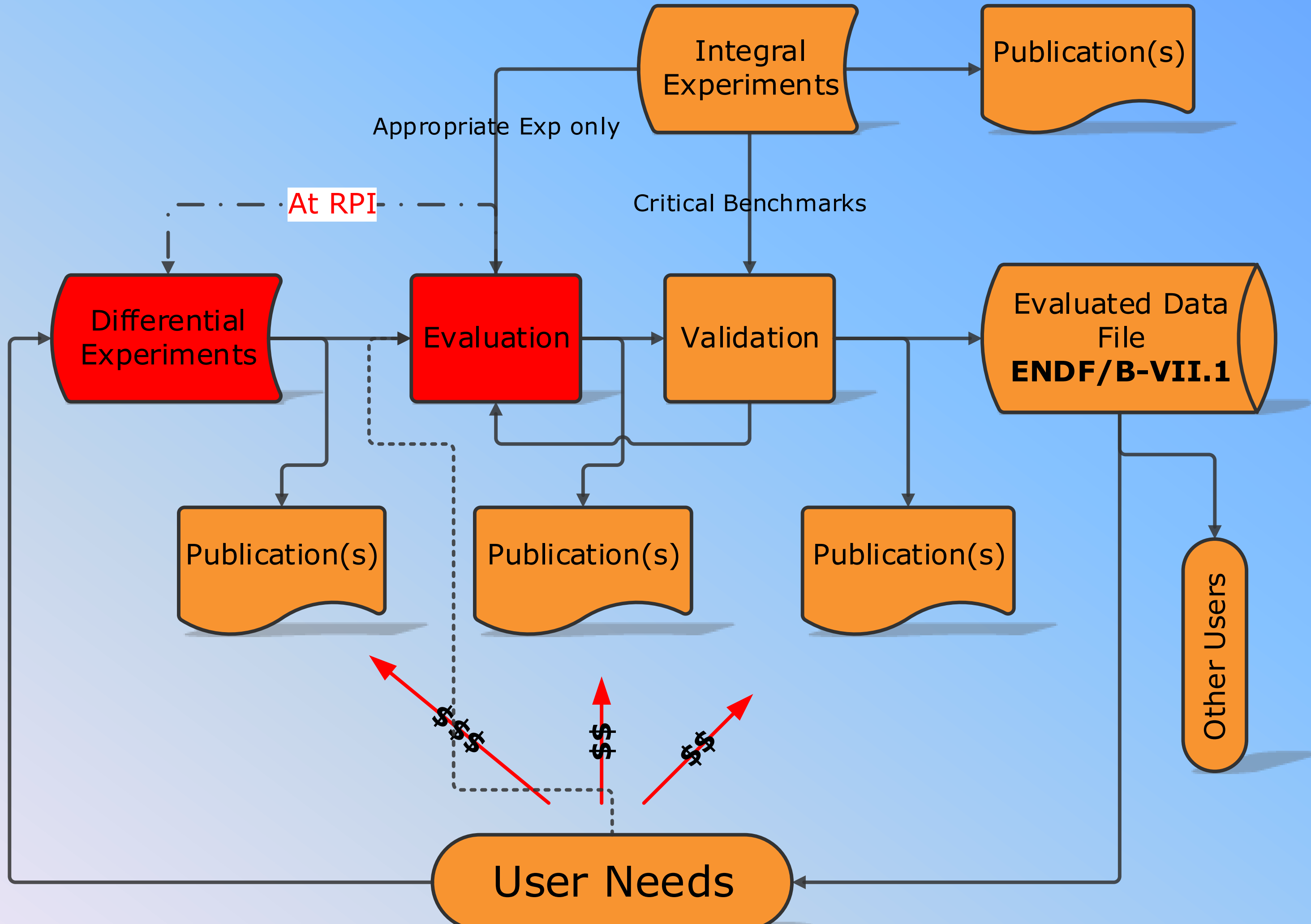
The Shippingport Reactor (Critical in 1957)
http://www.pabook.libraries.psu.edu/palitmap/Shippingport.html



- Effective neutron Multiplication factor
- Neutron flux
- Burnup
- Kinetics

Nuclear Data Lifecycle (Danon's view)

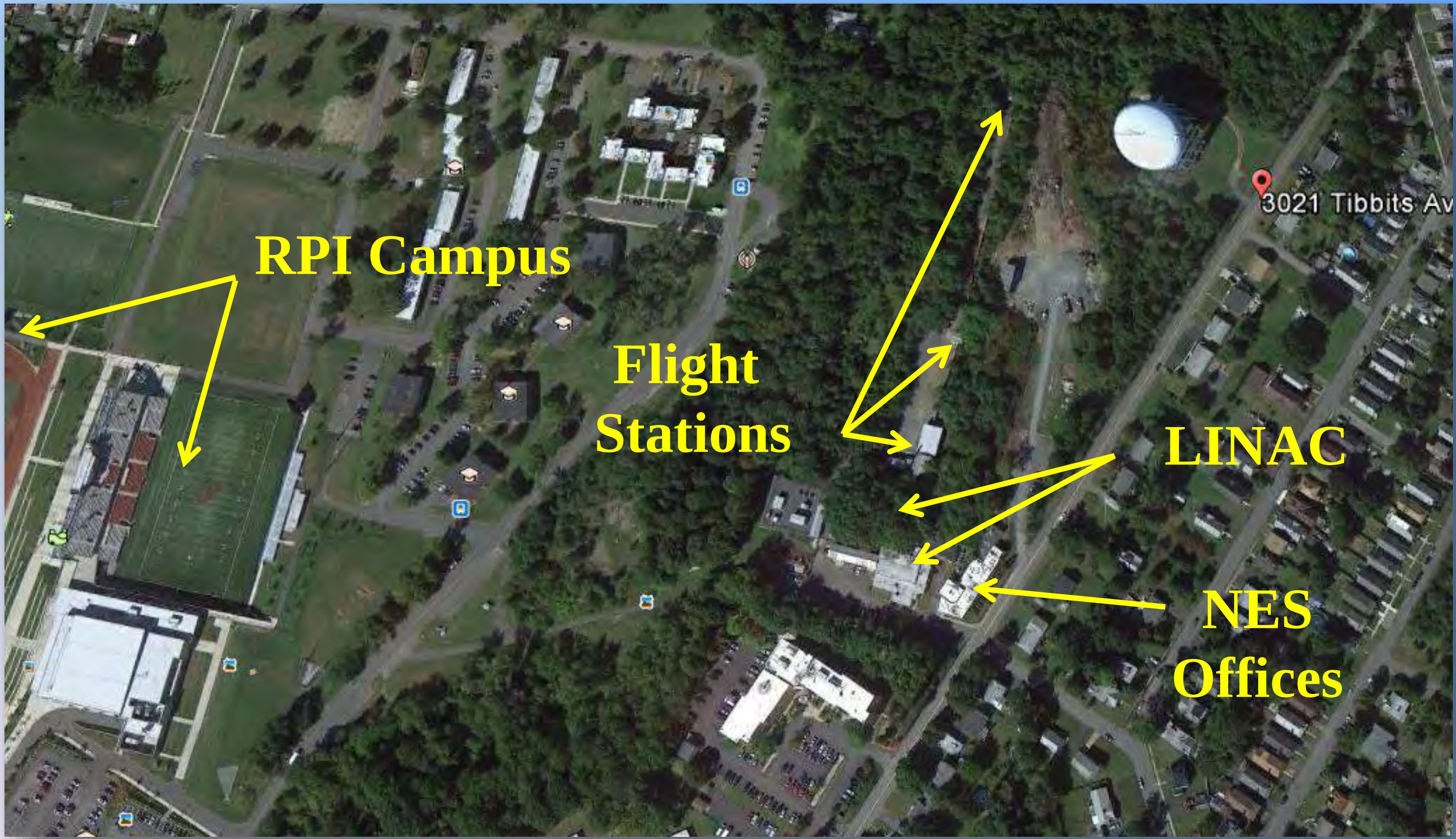
Application Driven



Applications

Where is the RPI LINAC ?

- It is on the highest point in Troy, NY



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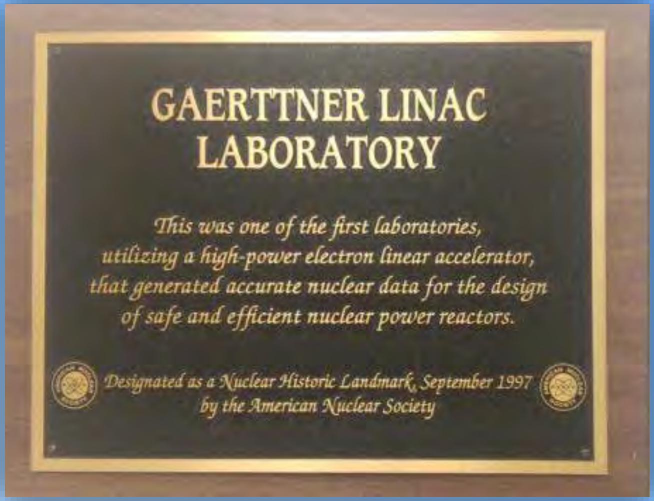
RPI LINAC History

- The RPI LINAC started operation in December 1961.
- Working “continuously” since.

September 1997- LINAC was designated as Nuclear Historic Landmark by the American Nuclear Society

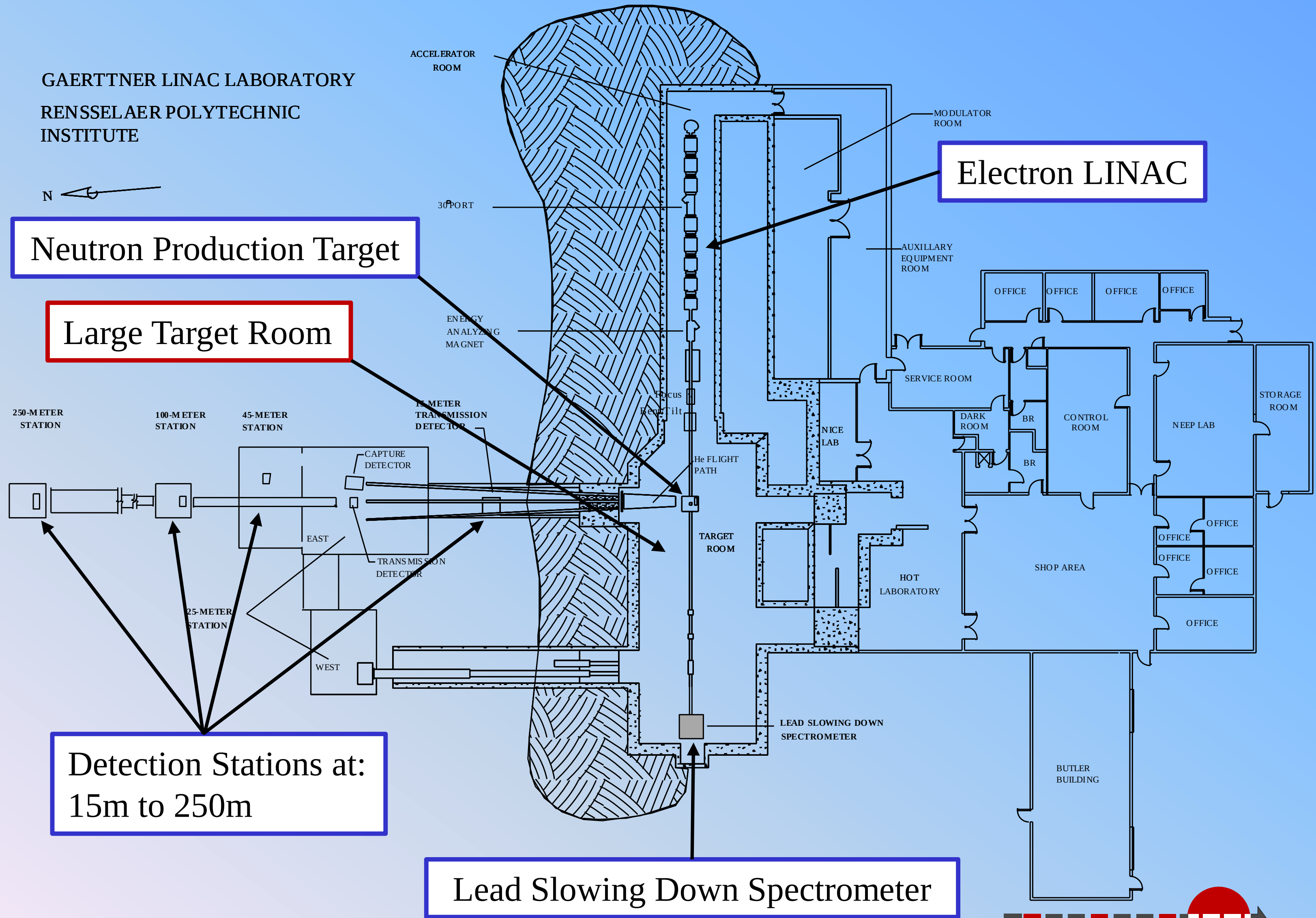


Graduated over 170 students who utilized the LINAC as part of their *PhD* thesis research

Many years of accumulated experience

2014 - Started a major refurbishment and upgrade project

The RPI LINAC Facility



LINAC Specifications 2015

	Three Sections (Low Energy Port)	Nine Sections (High Energy Port)
Electron Energy	5 to 25 MeV	25 to over 60 MeV
Pulse Width	6 to 5000 ns	6 to 5000 ns
Peak Current	3A (short pulse: 6 to 50 ns) 400 mA (long pulse: 50 to 5000 ns)	3A (short pulse: 6 to 50 ns) 400 mA (long pulse: 50 to 5000 ns)
Average Power	10 kw@ 17 MeV, 5000 ns	>10 kw@ 60 MeV, 5000 ns
Peak Dose Rate	$>10^{11}$ Rads/sec (in Silicon)	n/a
Neutron Production	n/a	**~4 X 10^{13} neutrons/sec**
Pulse Repetition Rate	Single pulse to 500 pps (short pulse) Single pulse to 300 pps (long pulse)	Single pulse to 500 pps (short pulse) Single pulse to 300 pps (long pulse)

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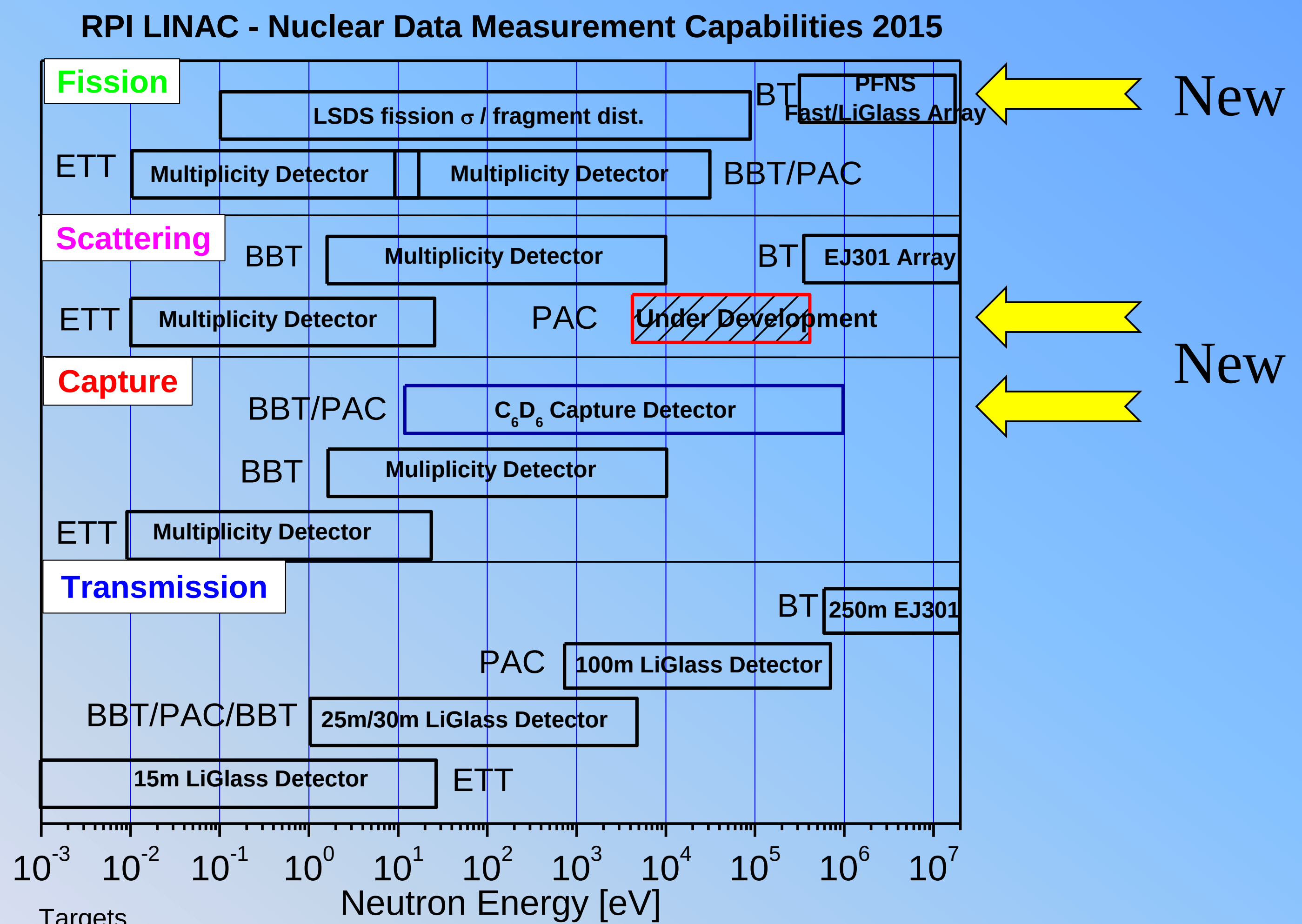
Capability Matrix and Development



Targets

ETT- Enhanced Thermal Traget

BBT - Bare Bounce Target

BT- Bare Target on Axis

PAC - PacMan Target

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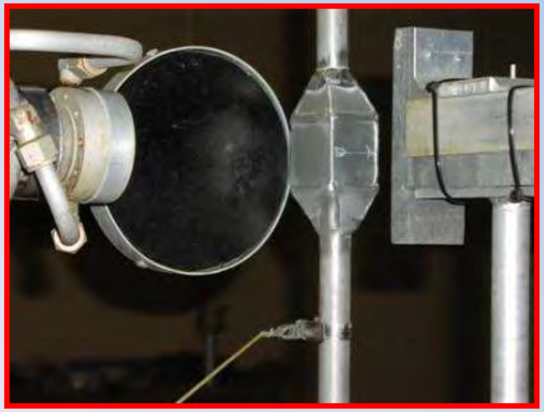
Neutron Production Targets

Bare Bounce Target (BBT)



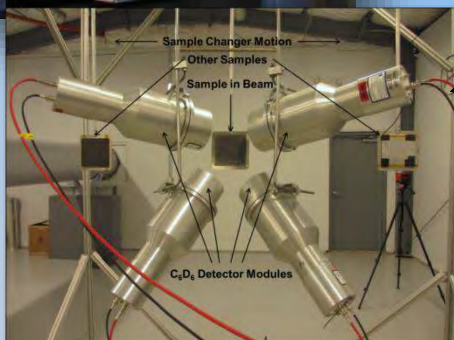
Enhanced Thermal Target (ETT)

PACMAN target

Detectors

25m

Capture/multiplicity



45m

Transmission

15m- 30m

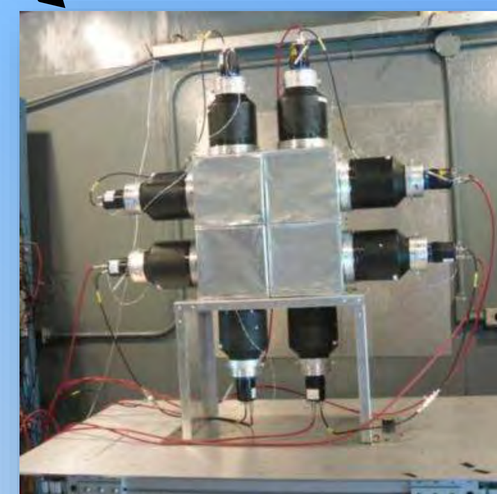
100m

250m

Scattering

PFNS

30m

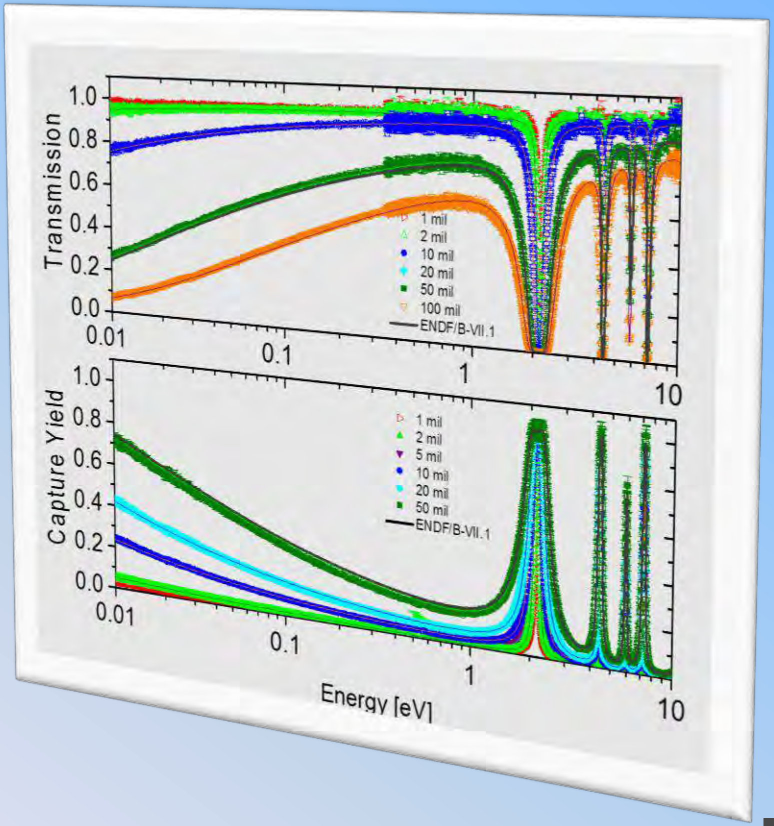


Current Activity

- **Time of flight measurements**
  - Resonance Region
    - Capture (0.01 eV – 2 keV)
    - Transmission (0.001 eV – 100 KeV)
    - Capture to fission ratio (alpha)
    - keV capture detector
    - Neutron scattering (E<0.5 MeV)
  - High energy (0.4-20MeV)
    - Scattering (30 m flight path)
    - Transmission (100m and 250m flight path)
    - Prompt Fission Neutron Spectra
  - High accuracy total cross section measurements using filtered beam

- **Lead Slowing Down Spectrometer**
  - Simultaneous measurement of fission cross sections and fission fragment mass and energy distributions using the RPI lead slowing down spectrometer
  - Measurements of energy dependent (n,p) and (n,α) cross sections of nanogram quantities of short-lived isotopes. (collaboration with LANL).
  - Capture cross section measurements
- **Other**
  - Research on medical isotope production
  - S(α,β) measurements (at SNS in ORNL)

Resonance Region



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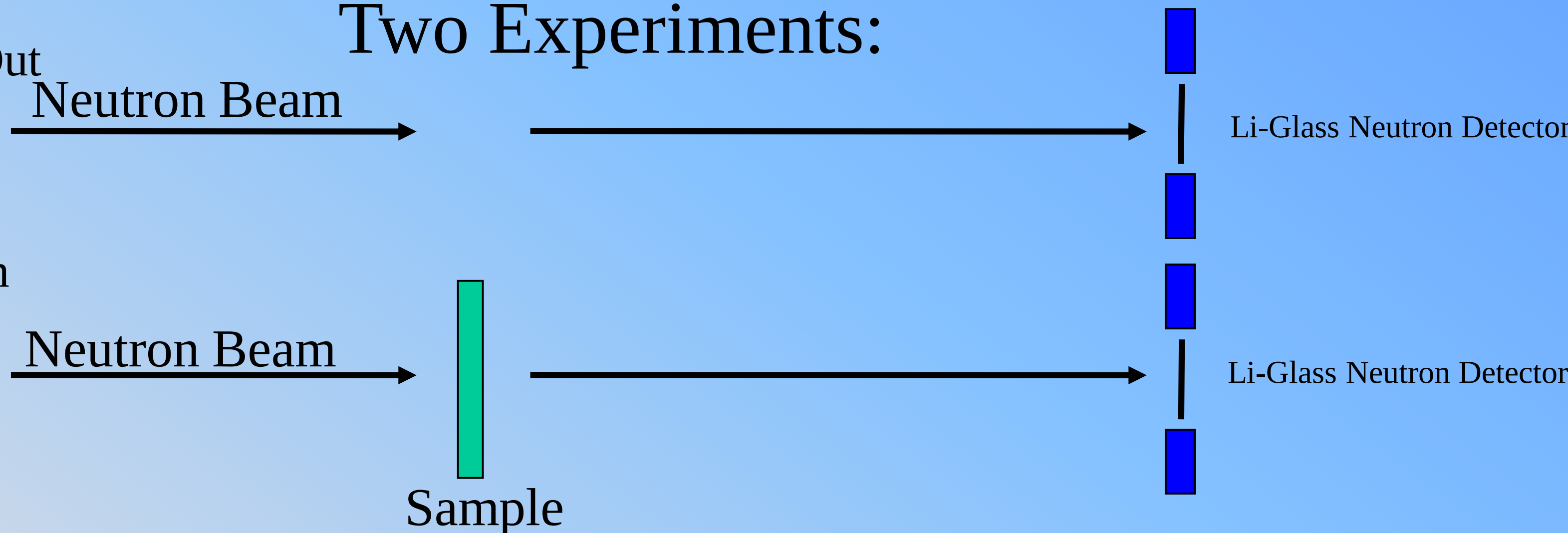
Transmission Experiment

Two Experiments:

1. Sample Out

2. Sample In

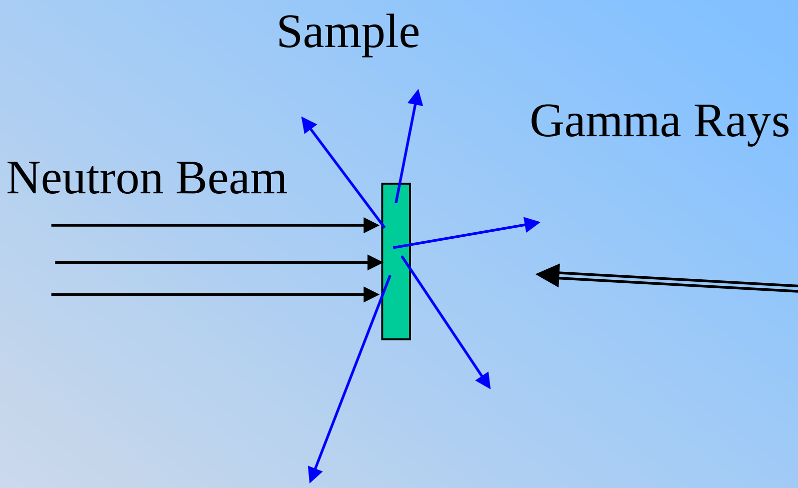


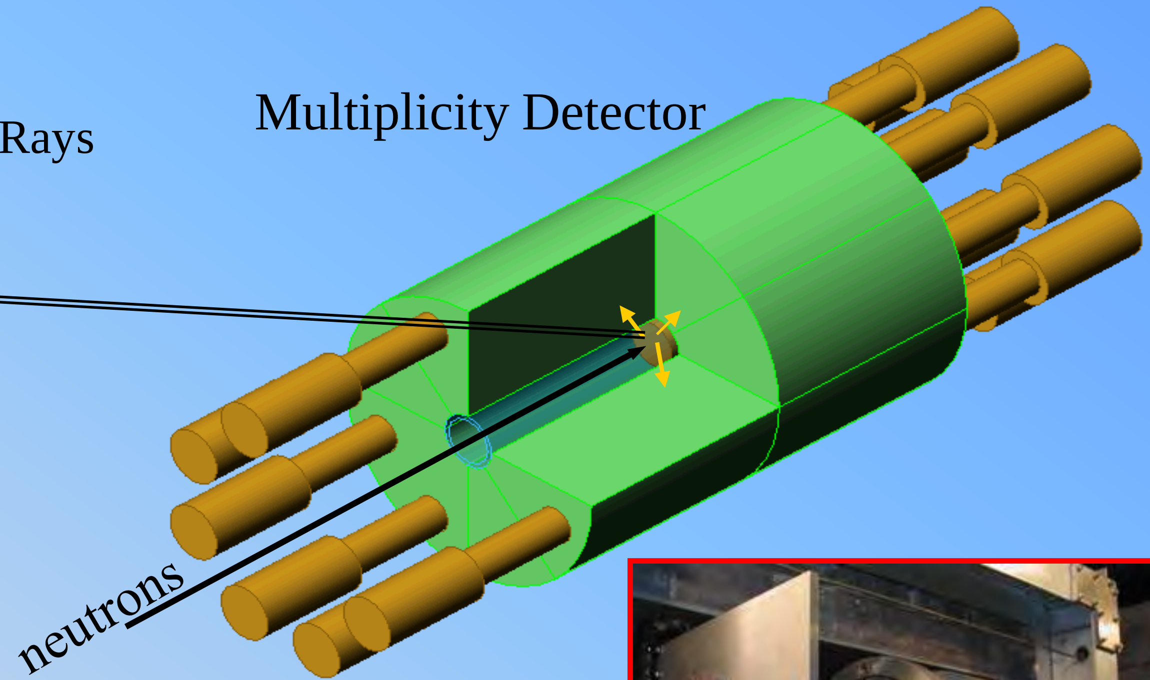
$$T = \frac{C_{\text{Sample In}}}{C_{\text{Sample Out}}} = \exp(-N\sigma_t)$$

N – Number density [atoms/barn]

σ_t – Total cross section

Capture Experiments





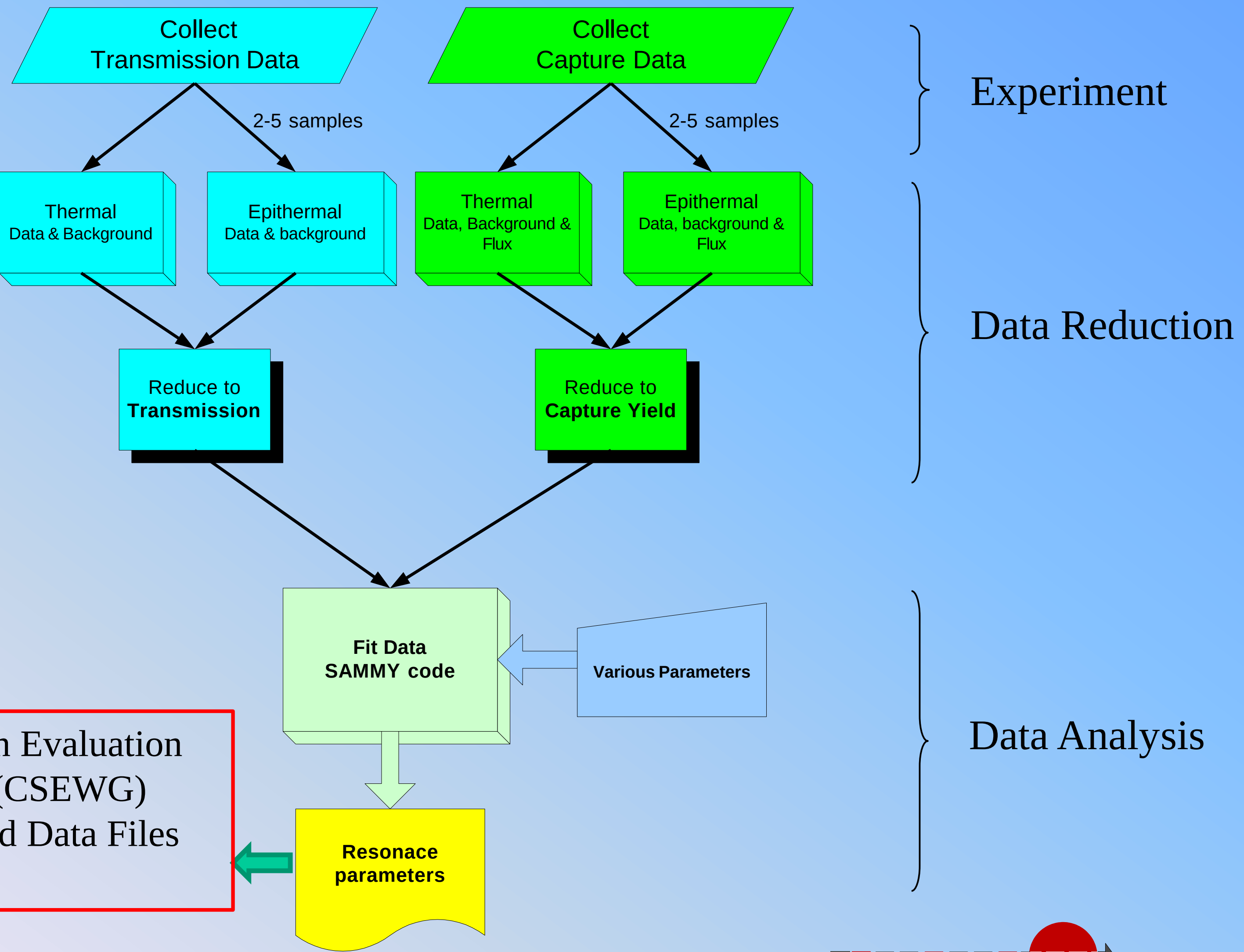
The capture Yield:

φ – neutron flux
η – detection efficiency

$$Counts = \phi Y \eta$$

$$Y = \left(1 - \exp(-N\sigma_t)\right)\frac{\sigma_\gamma}{\sigma_t}$$

Resonance Cross Section Measurements
Data Analysis



- US Cross Section Evaluation Working Group (CSEWG)
- **Users -** Evaluated Data Files ENDF/B-VII.1

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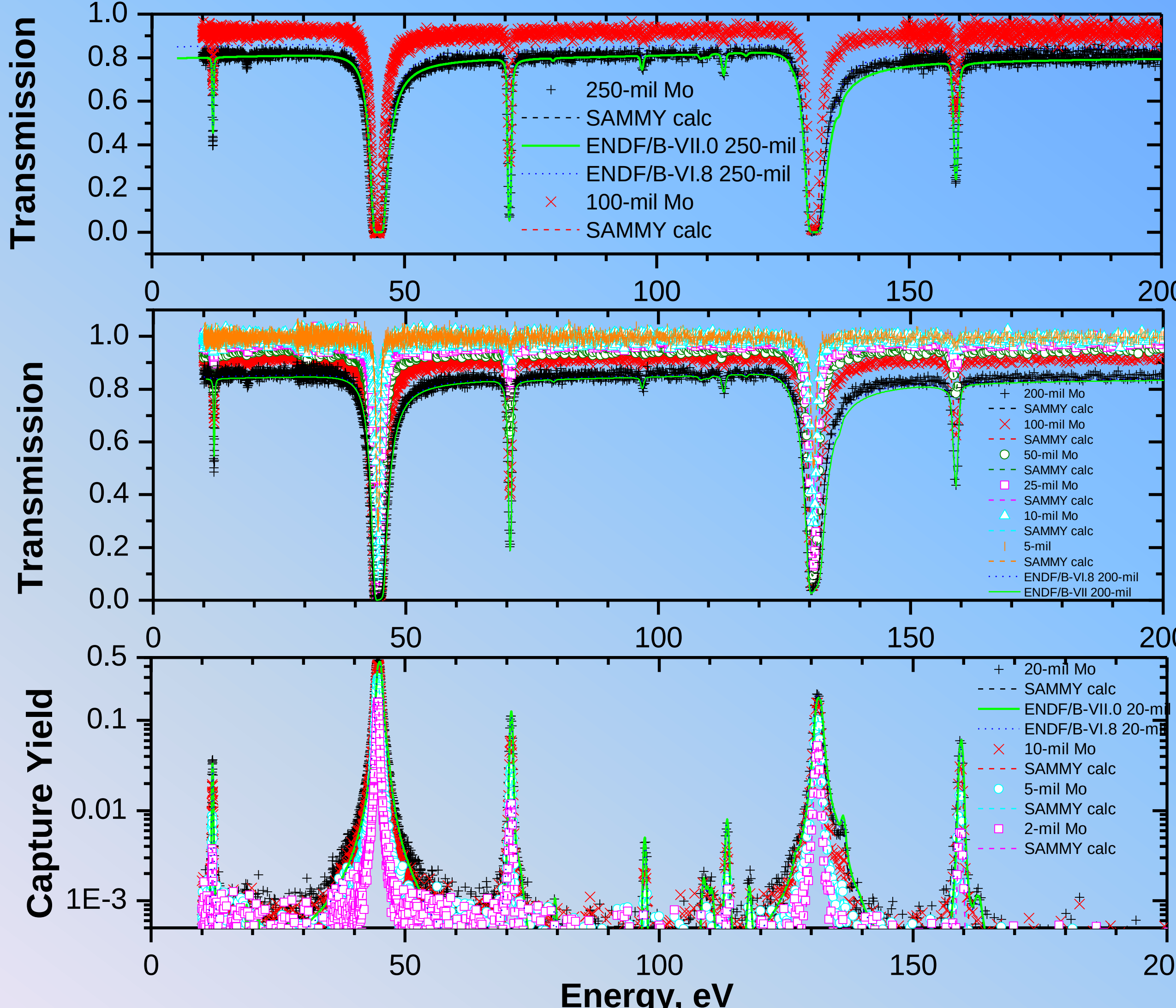
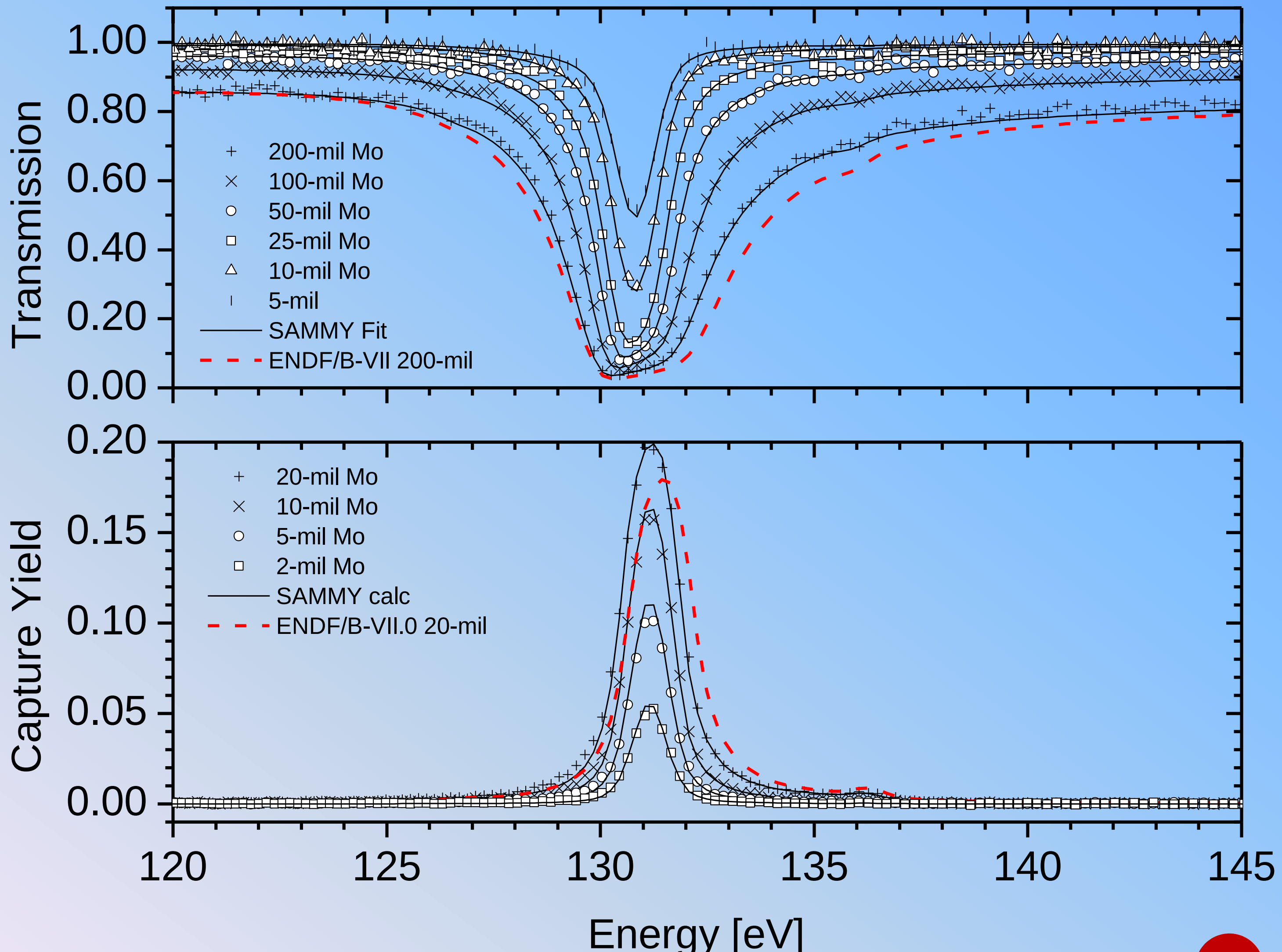
Elemental Molybdenum



Elemental Molybdenum 120 eV - 145 eV



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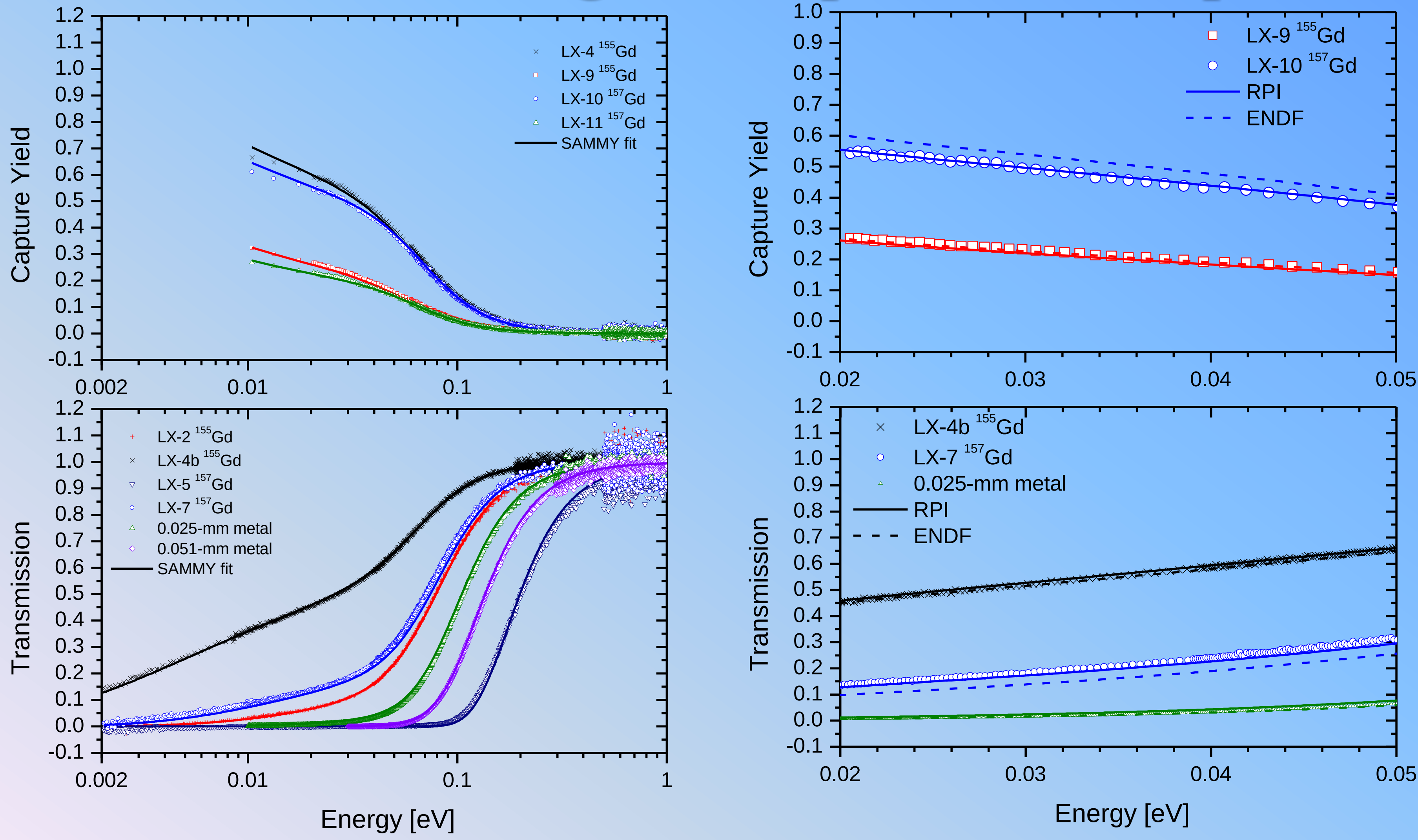
Gd Thermal Region - Separated Isotopes



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^{235}U Capture & Fission Yield Data - Epithermal Measurement

- Challenges:
  - Normalization
  - False capture due to neutron scattering

➢ Normalize experimental fission yield to resonance

$$\boxed{Y_f^{ENDF} = k_1 \cdot Y_f} \qquad \text{Solve for } k_1 \text{ @ 19.3 eV res} \quad \left(\frac{\Gamma_f}{\Gamma} = 0.63\right)$$

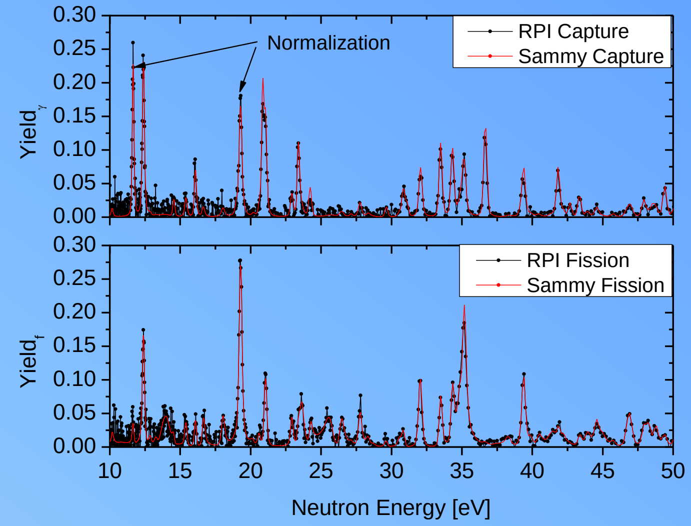
➢ Use two equations for predominantly capture and fission resonances

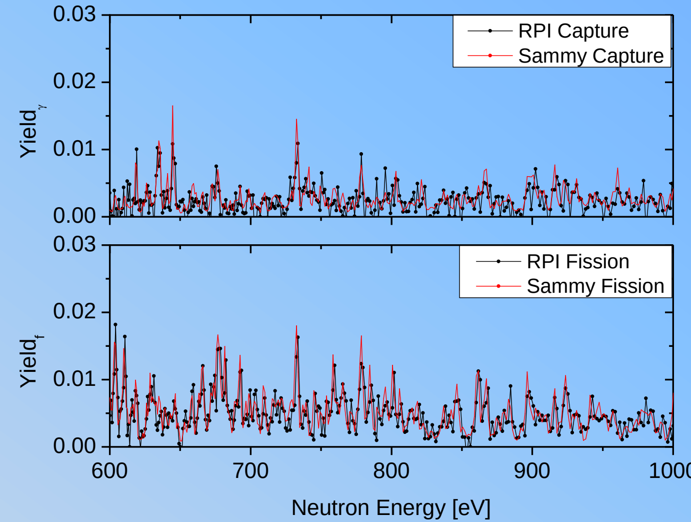
@ 11.7 eV res $\left(\frac{\Gamma_\gamma}{\Gamma} = 0.86\right)$ @ 19.3 eV res $\left(\frac{\Gamma_f}{\Gamma} = 0.63\right)$

$$\boxed{Y1_\gamma^{ENDF} = k_2 \cdot Y1_\gamma - k_3 \cdot k_1 \cdot Y1_f} \quad \boxed{Y2_\gamma^{ENDF} = k_2 \cdot Y2_\gamma - k_3 \cdot k_1 \cdot Y2_f}$$

➢ Solve the two equations for k_2 and k_3

► **Need 2 resonances with known parameters** ◄





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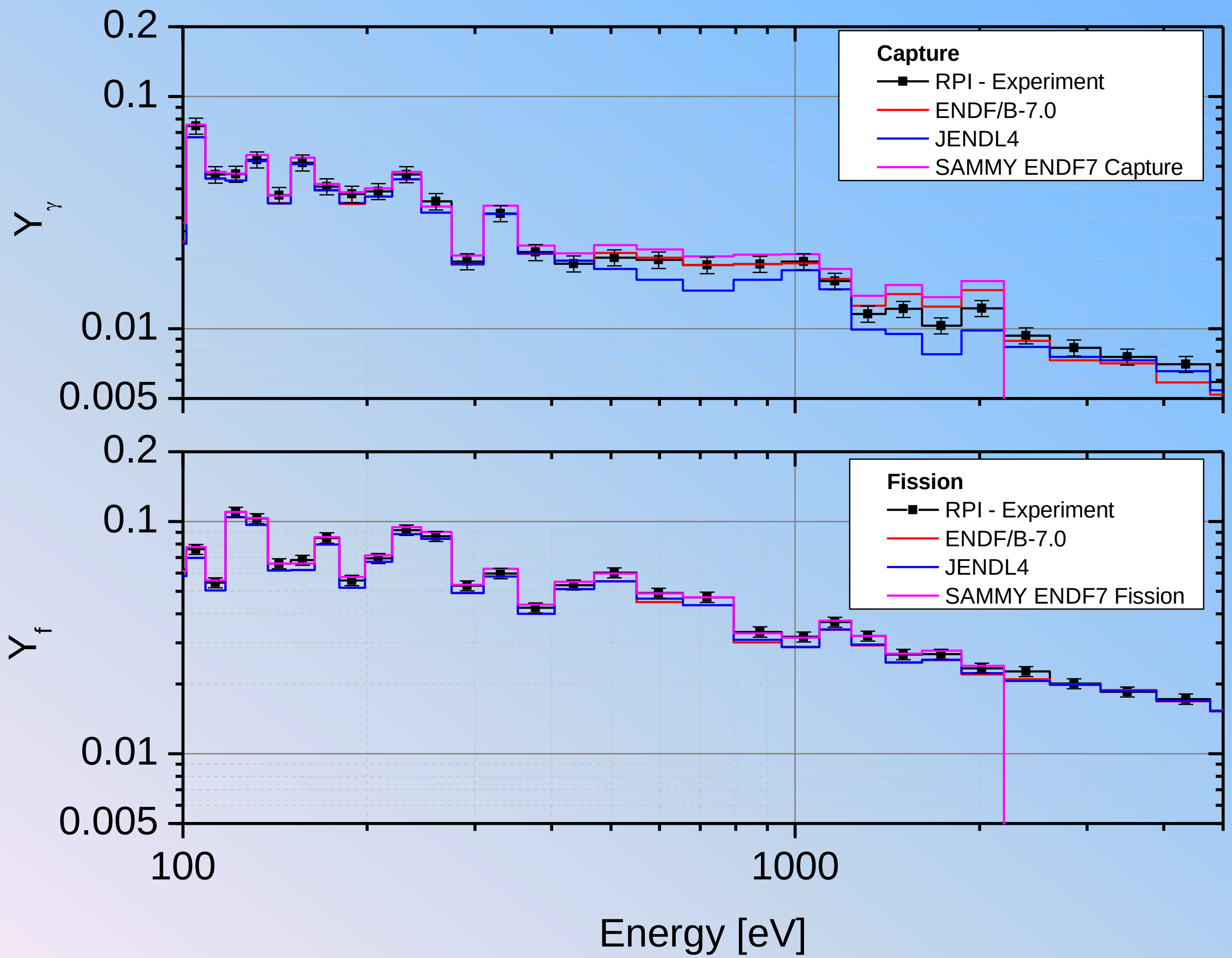
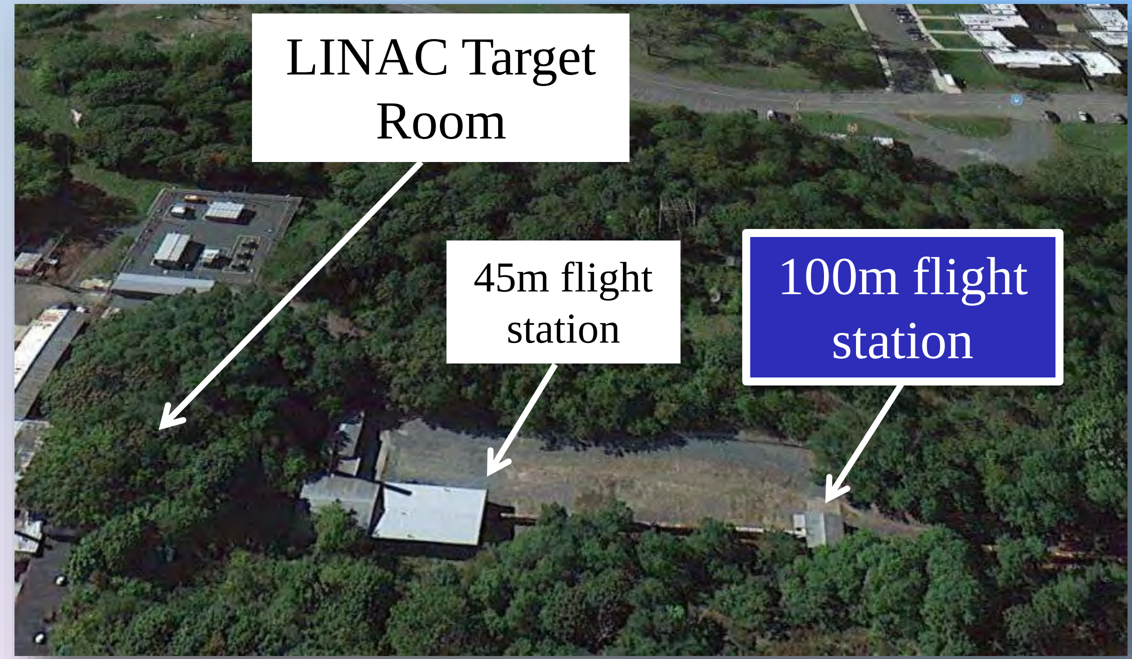
Comparing ^{235}U Fission and Capture with Evaluations

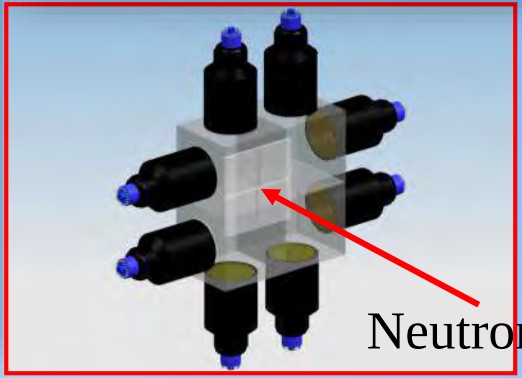


- Fission is in excellent agreement with evaluations
- Capture data has up to 8% multiple scattering that must be taken into account during the analysis
- Capture error is about 8%
- **0.4-1 keV capture data is closer to ENDF/B-7.0**
- **1-2 keV ENDF/B7.0 too high JENDL 4.0 too low.**
- **E>1 keV data is slightly higher than evaluations but within errors.**

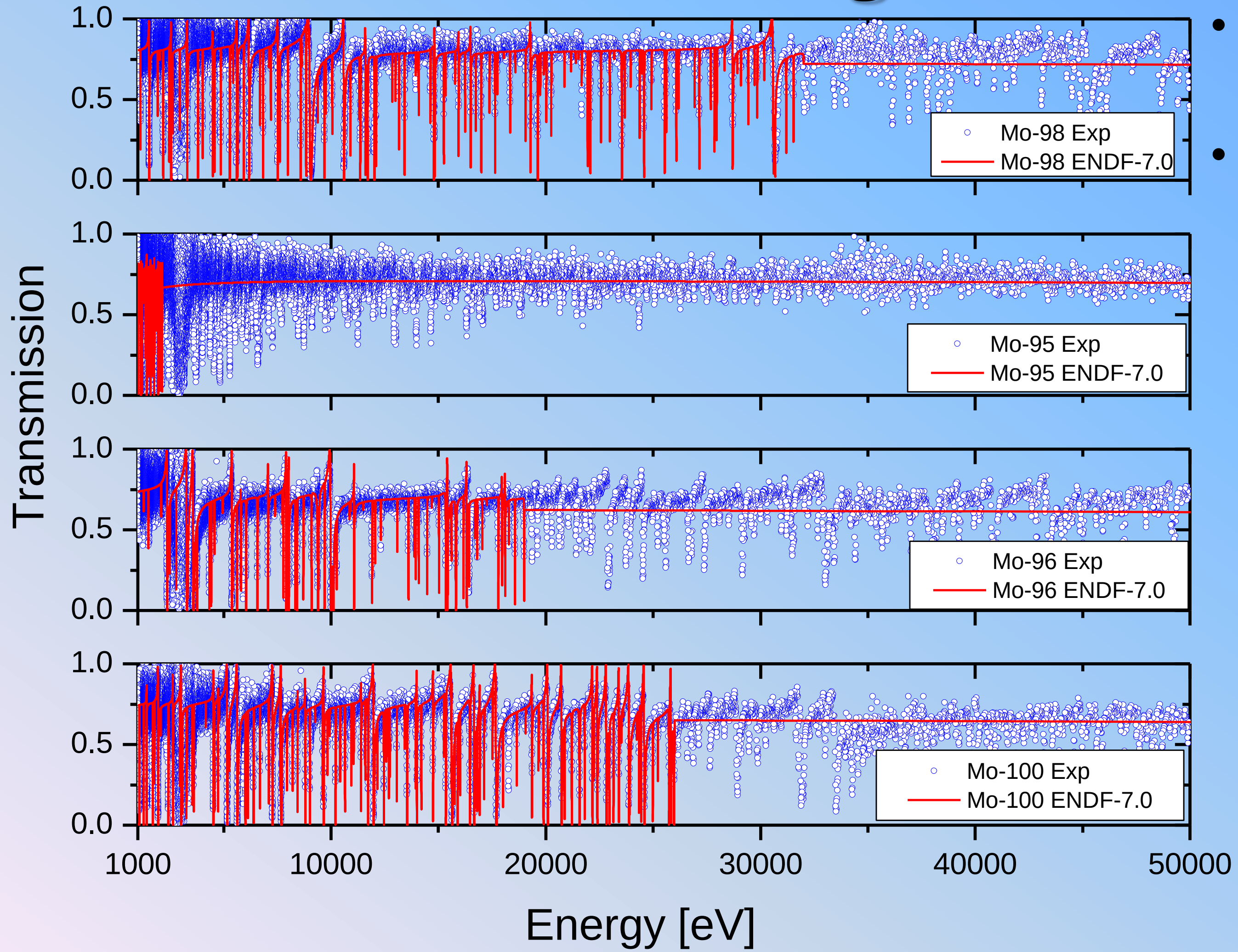
High Resolution Transmission Detector

- Modular Li-Glass detector at 100m flight path
  - Extends our capabilities to the unresolved resonance region
  - Measurement of $^{95,96,98,100}Mo$ completed.





Mo Isotopes in the Resonance Region 100m Flight Path



- Resonance parameters analysis in progress
- Data provide information to extend the resolved resonance region of several isotopes

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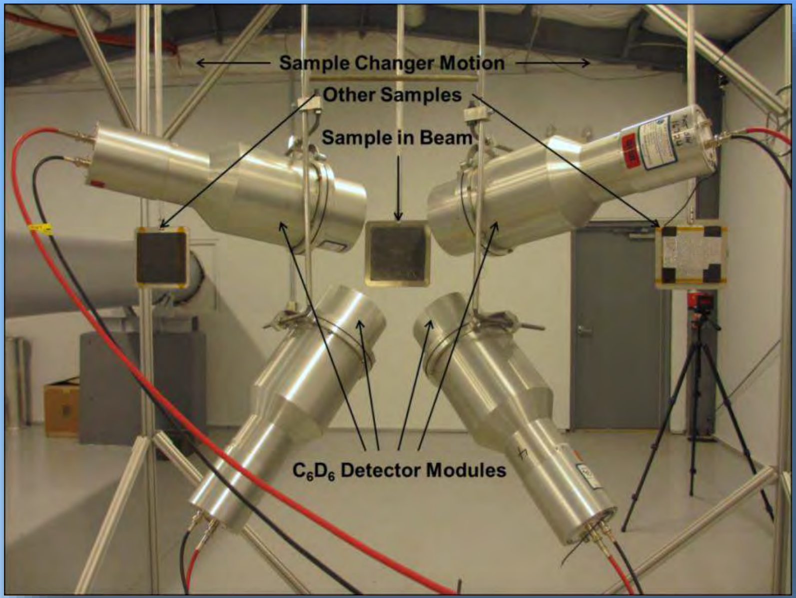
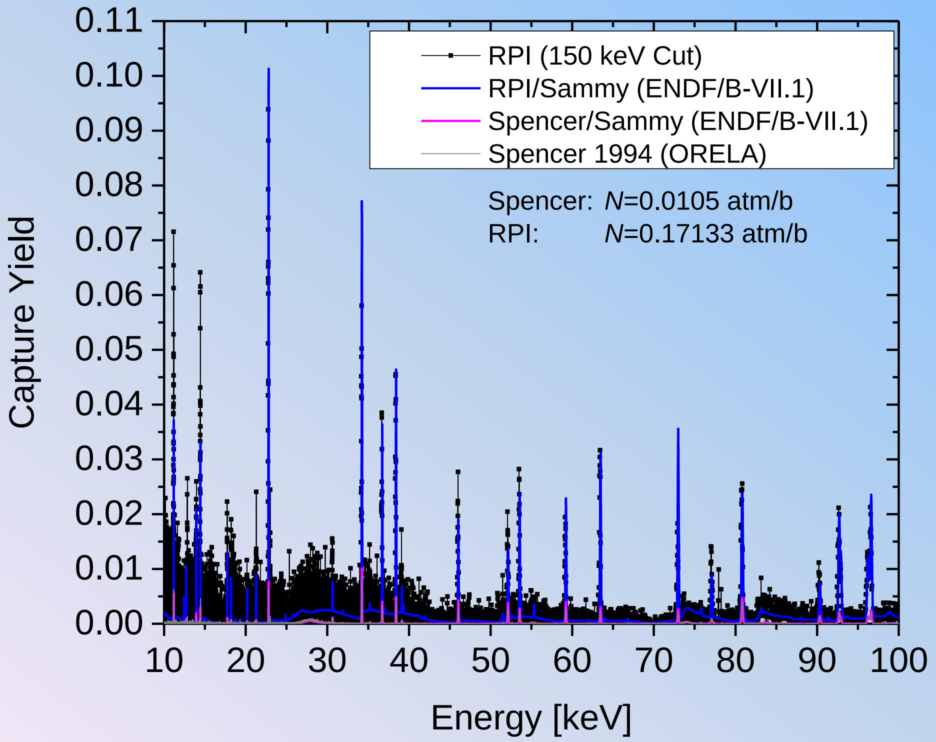
Mid-Energy Capture Detector System Overview

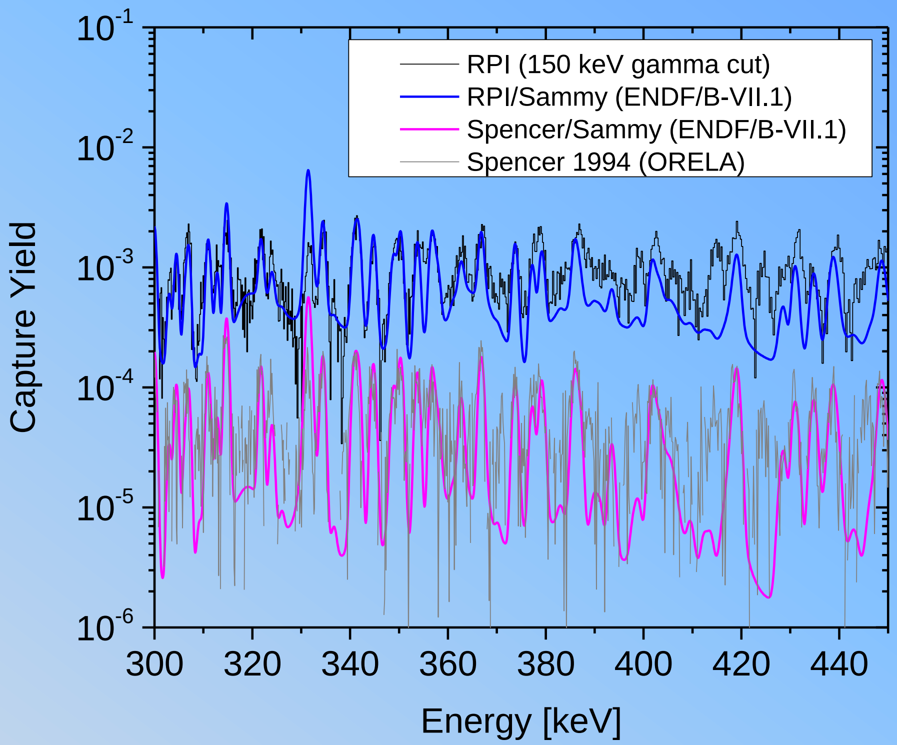
- 4 C_6D_6 detector modules manufactured by Eljen Technology
- **Low mass, low neutron sensitivity design**
- Located at 45m flight path in newly constructed flight station
- Measurements made from 1 eV to 1 MeV
- Requires a weighting function



^{nat}Fe Capture measurement

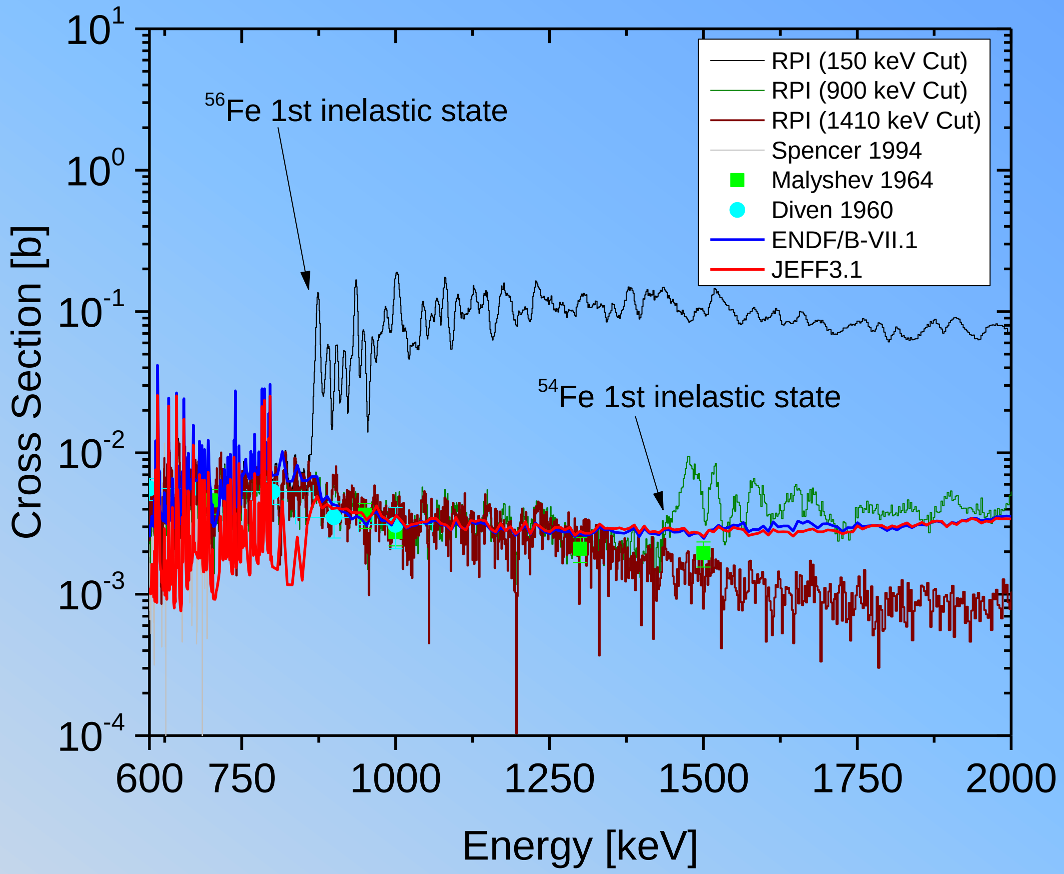
- ^{nat}Fe was used as a test to compare with evaluations and other measurements
  - The RPI data (45m flight path) has good energy resolution compared to the Spencer ORELA data (40m flight path)
  - The RPI data provide information above 700 keV (next slide)



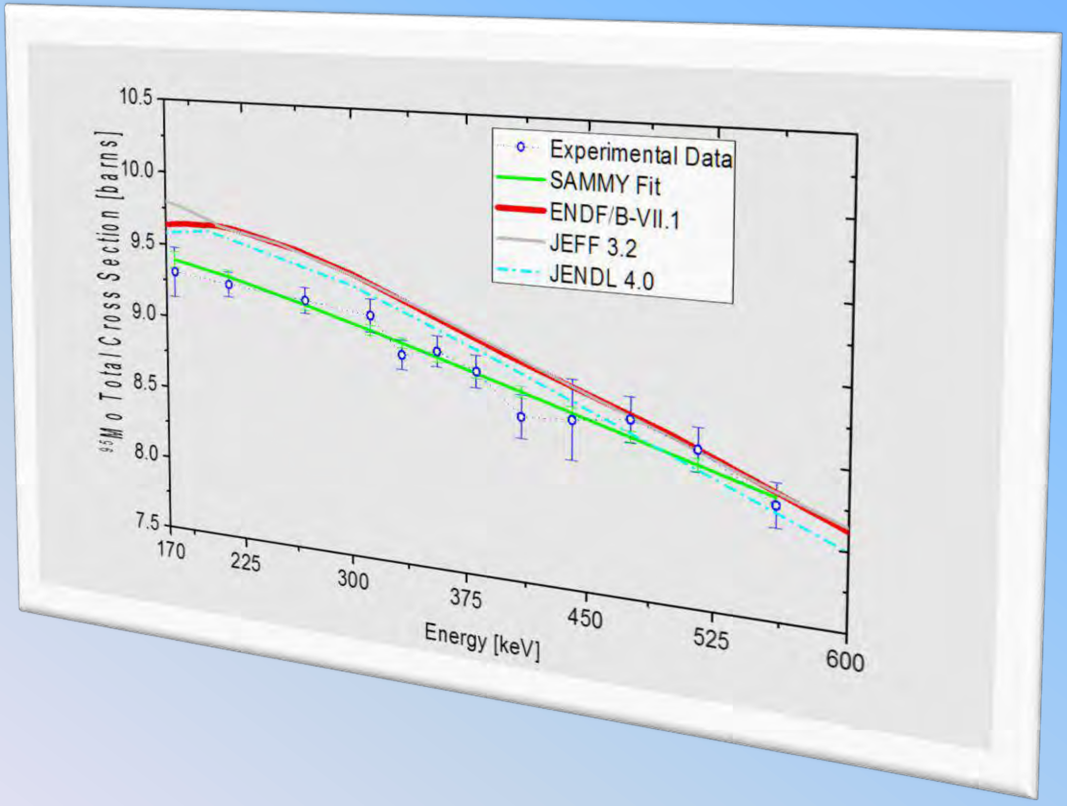


^{nat}Fe Capture Cross Section above 847 keV

- New capture data obtained above 847 keV and 1409 keV inelastic states in ^{56}Fe and ^{54}Fe
- Capture signal separated from inelastic scattering signal by post-processing digitized waveforms with different energy deposition cutoffs
- Good agreement with other experiments
- The data is lower than the evaluations above 1400 MeV

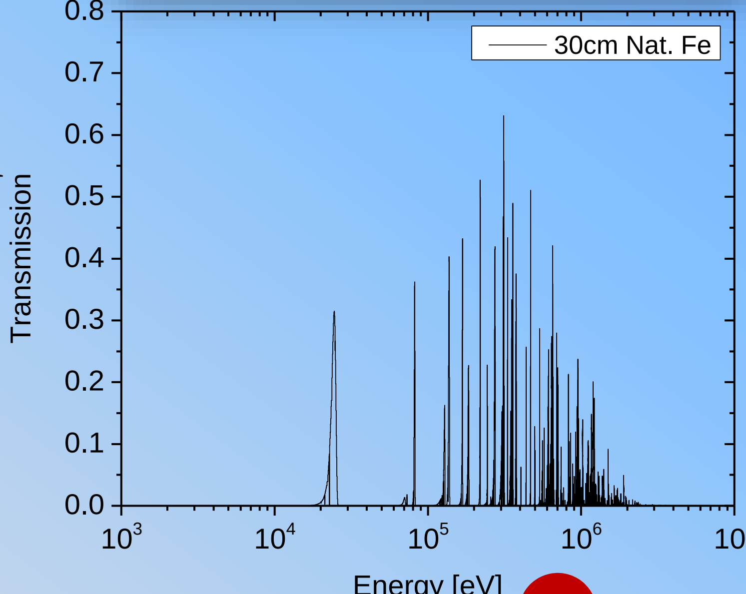


Unresolved Resonance Region



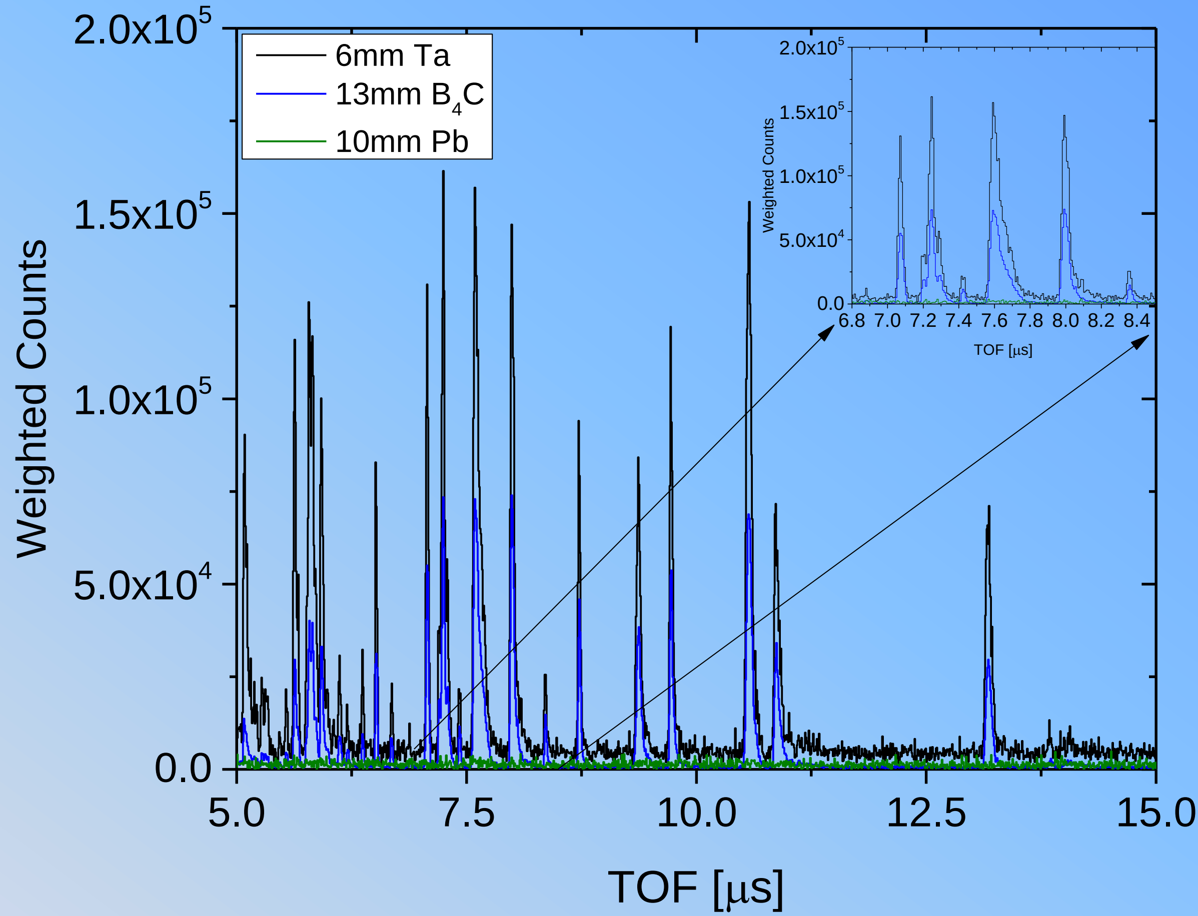
New Method – Fe Filtered Beam Capture Results for ^{181}Ta

- Measurements performed on ^{181}Ta using Fe-filtered beam technique
- 30cm thick Fe filter removes all beam-related gamma and neutron background
- Provides a quasi-monoenergetic neutron source corresponding to deep minima in the Fe cross section



Mid-Energy Capture Detector Experimental Results-^{181}Ta

- Count rates for Ta and B_4C samples were summed under each filter transmission peak.
- Pb scattering sample used to confirm negligible neutron background



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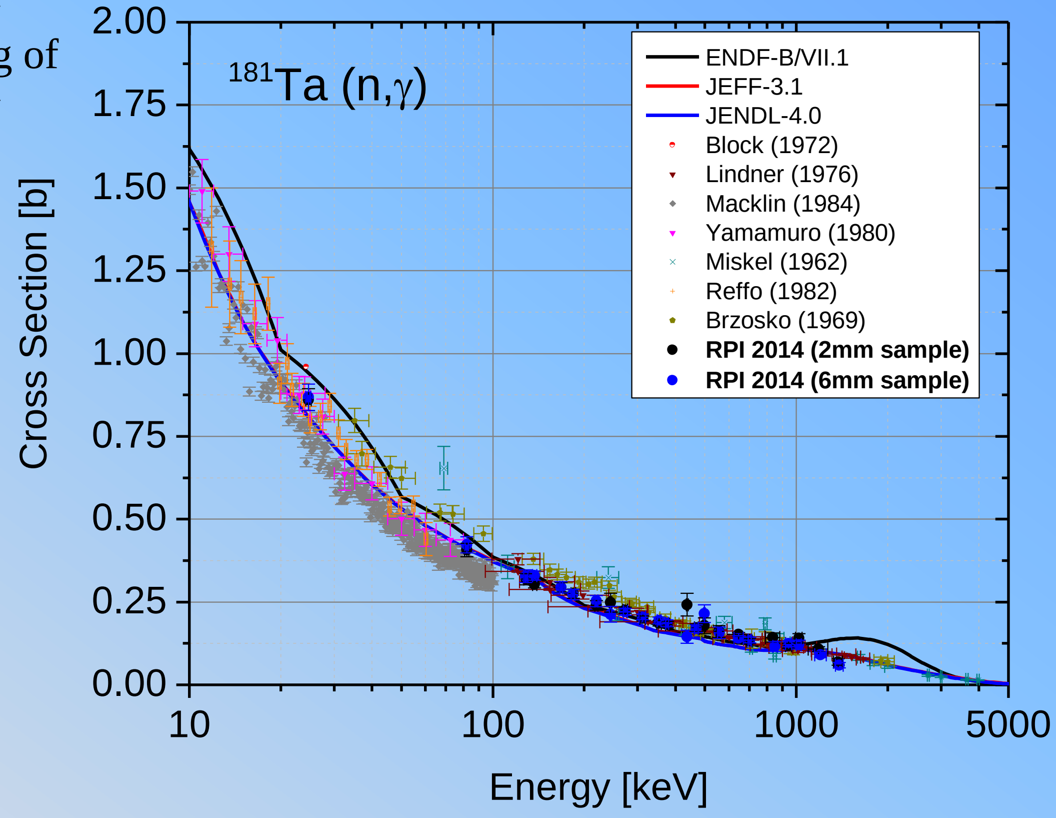
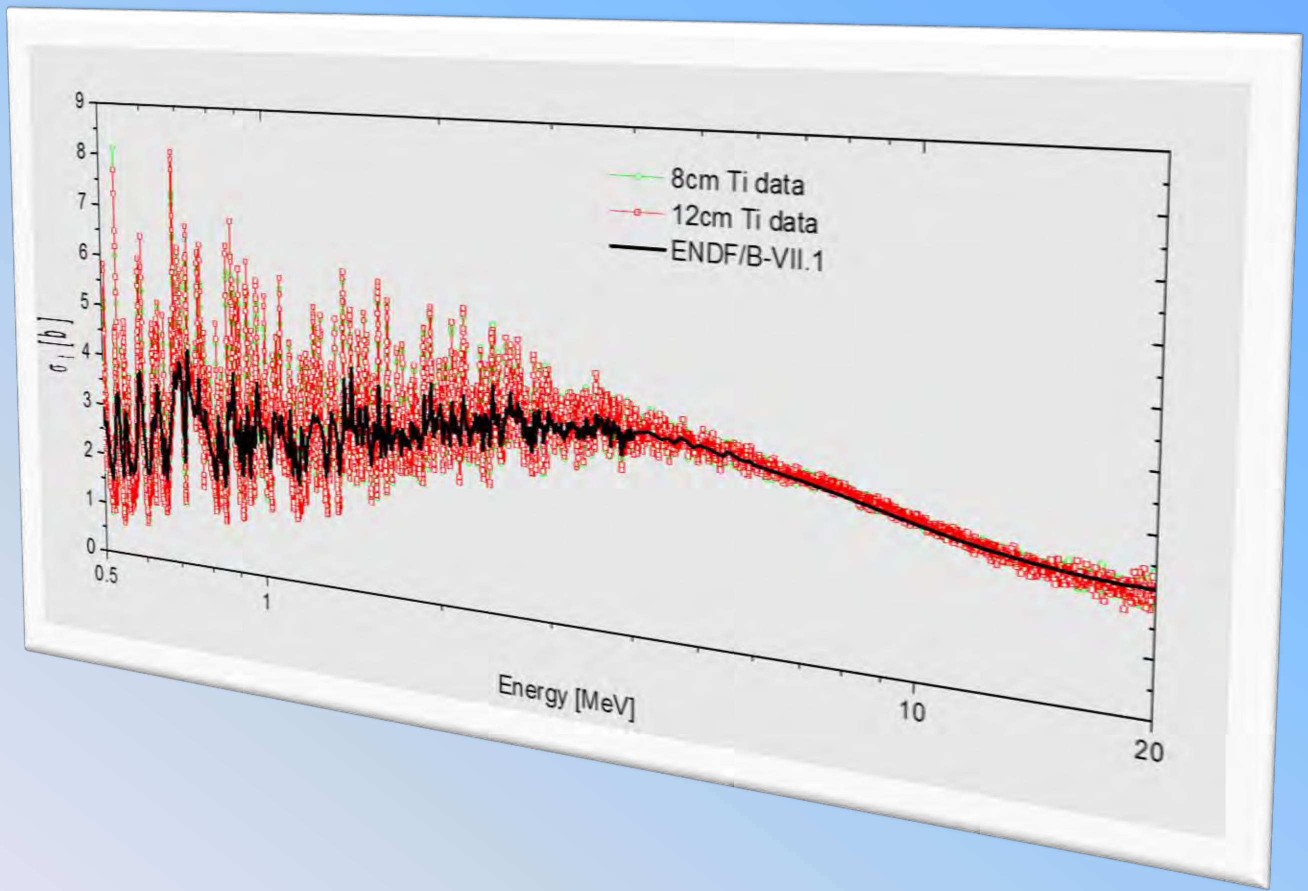
^{181}Ta Iron Filtered Beam Capture Measurement: Cross Section

- As expected thick sample=problems
  - Self shielding correction is high
  - Multiple scattering correction is high
  - Need to work on better understanding of the weighting function and it validity
- Thin sample support the JEFF-3.1/3.2 evaluation
- Possible contamination from inelastic scattering apparent in ENDF/B-VII.1



Fast Region



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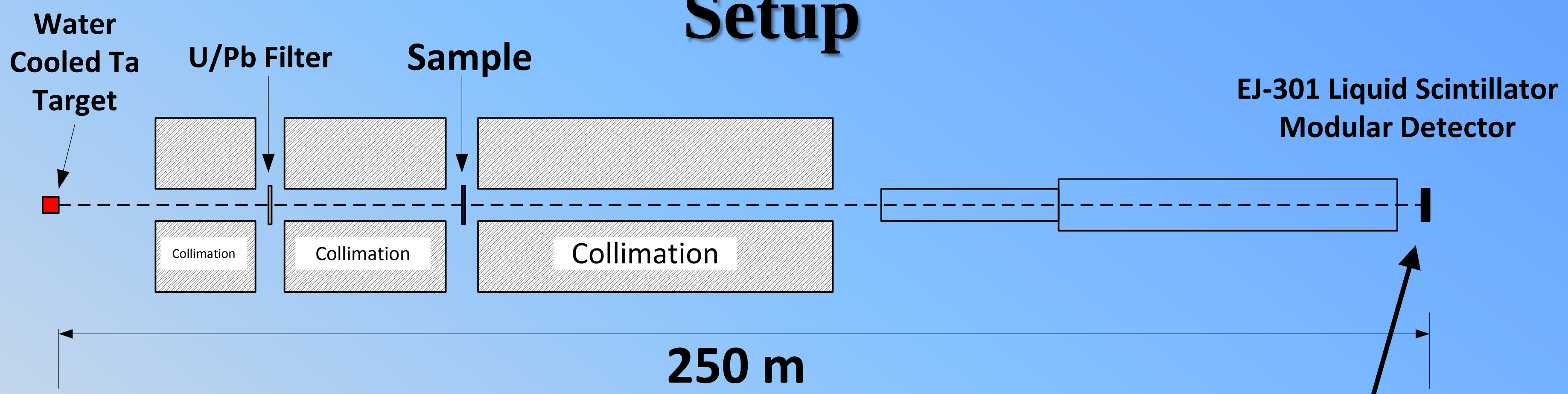
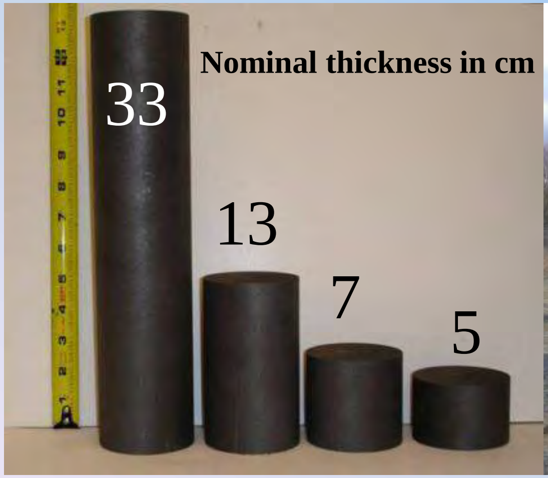
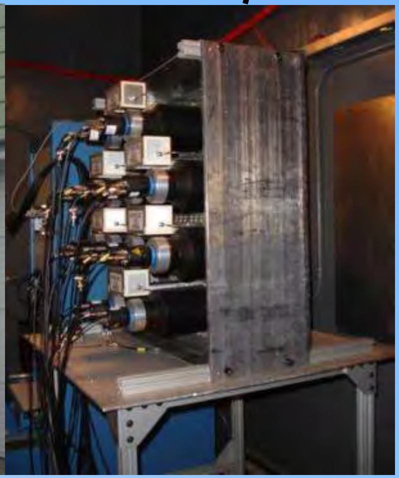
High Energy Transmission Experimental Setup

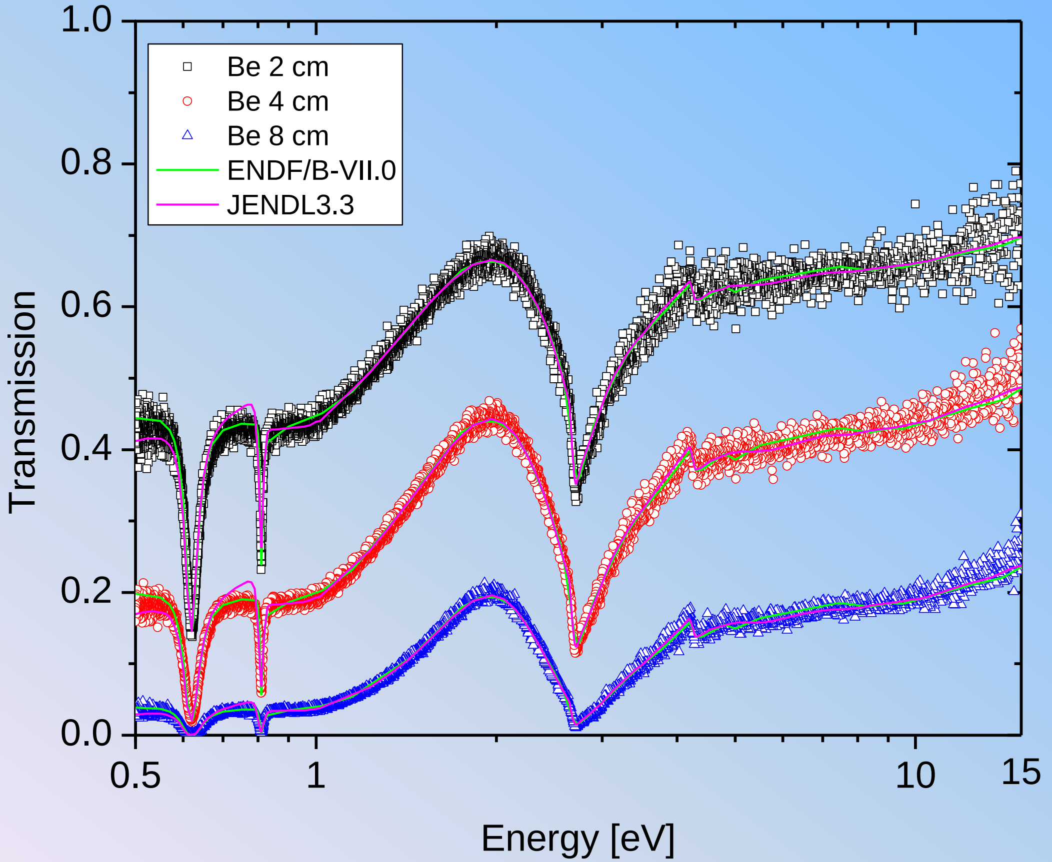


Graphite Samples





Beryllium Transmission

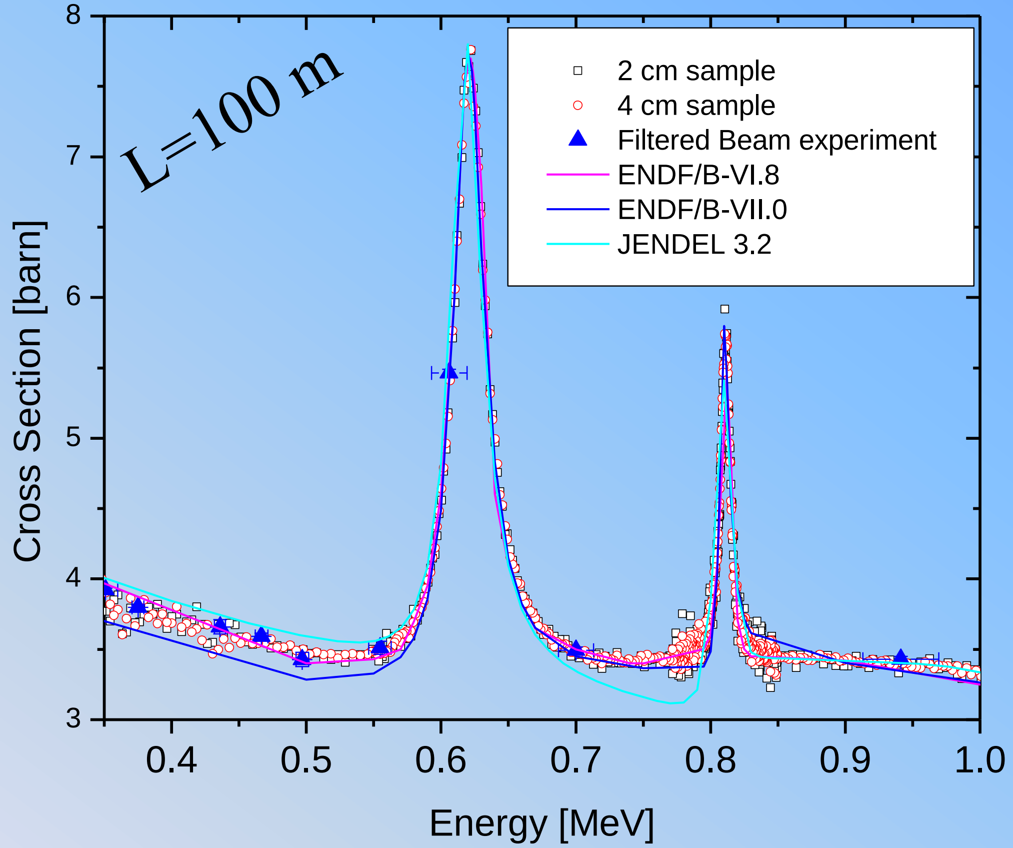


Beryllium samples

Sample thickness is given in cm

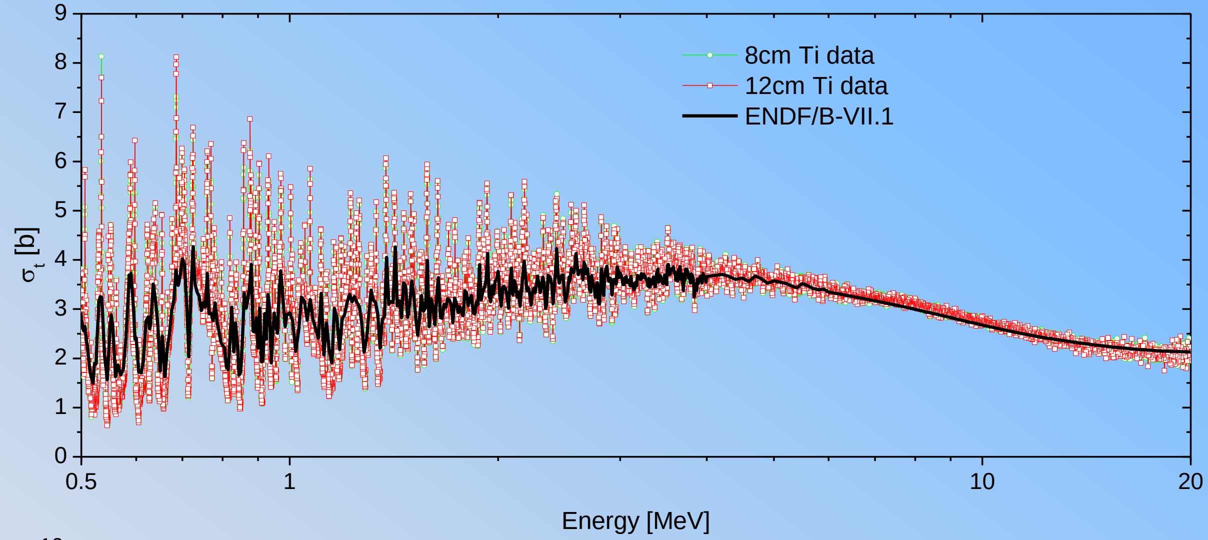
Reconfigured the detector with two units to reduce background

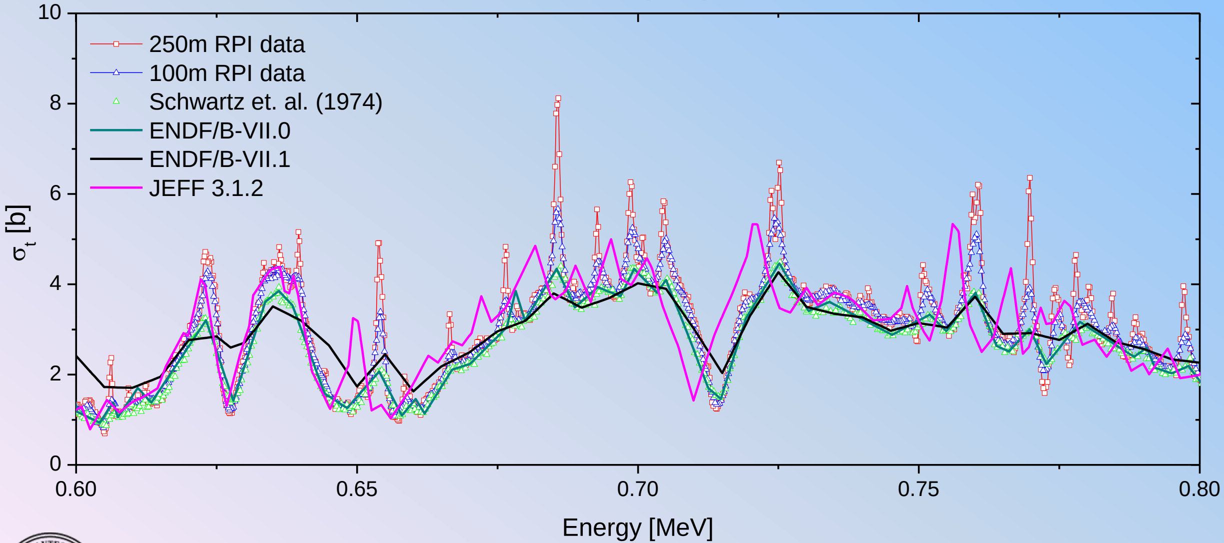
Beryllium Total Cross Section (Low Energy)



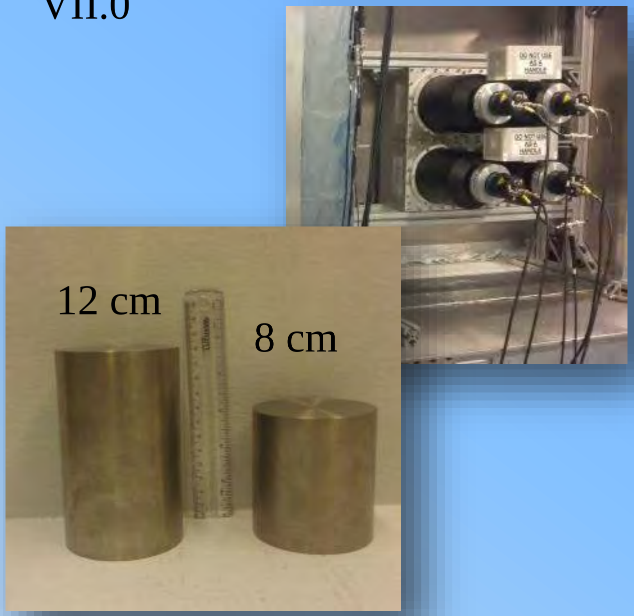
M.J. Rapp, Y. Danon, F.J. Saglime, R.M. Bahran and D.G. Williams, G. Leinweber, D.P. Barry and R.C. Block, “Beryllium and Graphite Neutron Total Cross Section Measurements from 0.4 to 20 MeV”, Nuclear Science and Engineering, Vol. 172, No. 3. Pages 268-277, November 2012 (2012).

Ti Total Cross Section Measurements 0.5 – 20 MeV

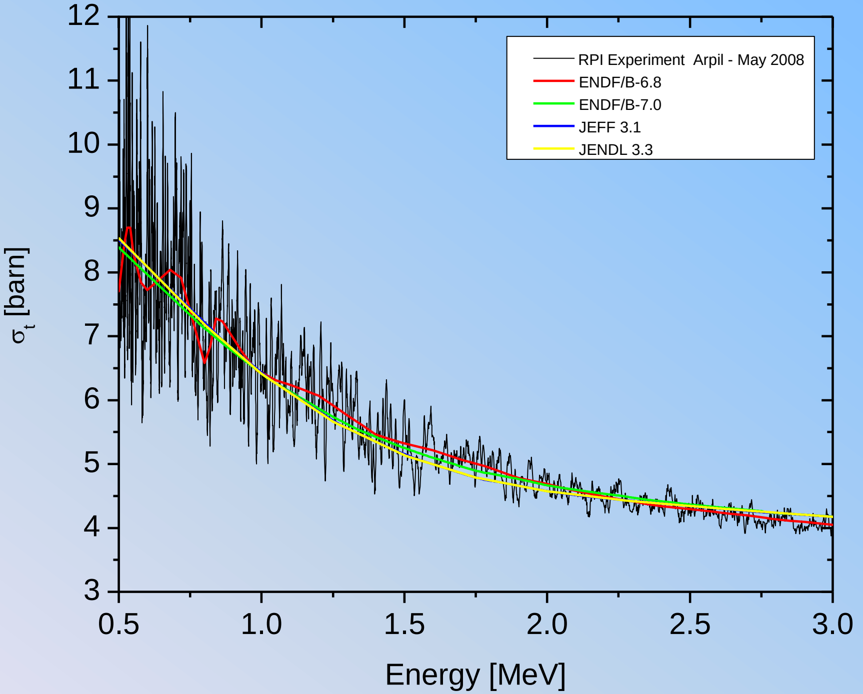


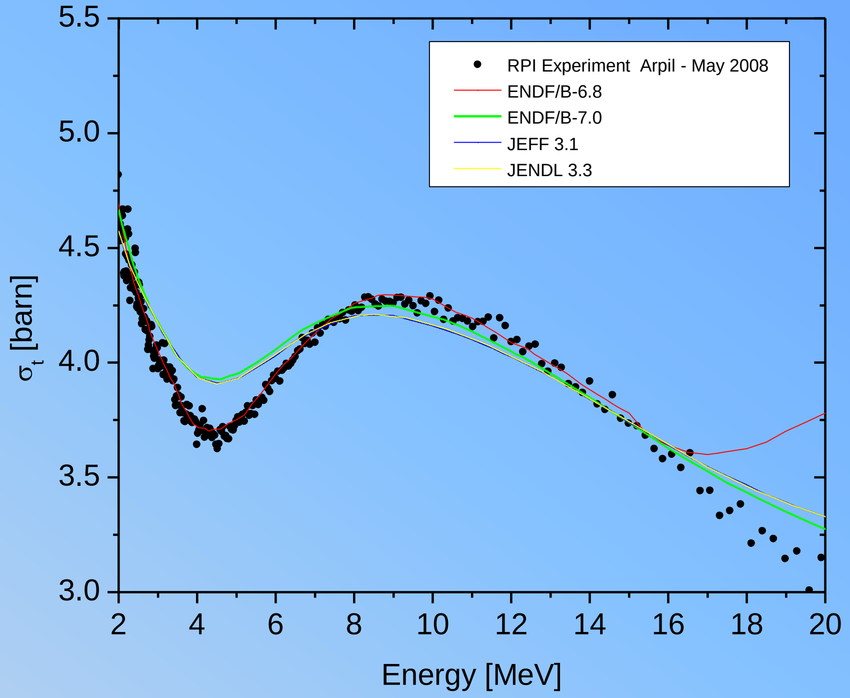


- 250m flight path measurement shows structure that was not resolved in prior measurements
- JEFF 3.1.2 shows an energy shift
- ENDF/B-VII.1 lower resolution than JEFF 3.1.2 and ENDF/B-VII.0

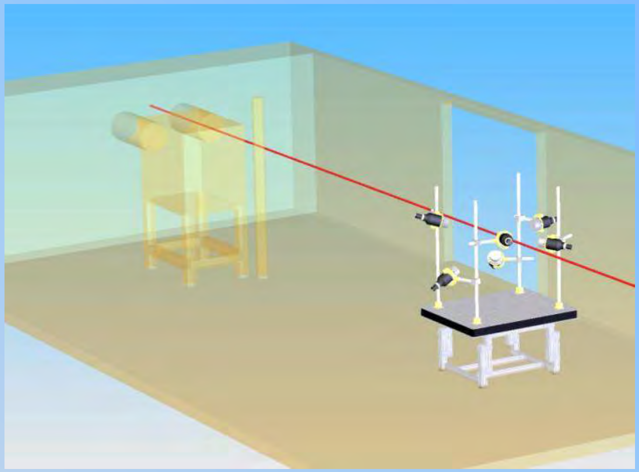


Zr Total Cross Section Measurements (0.5-20 MeV)



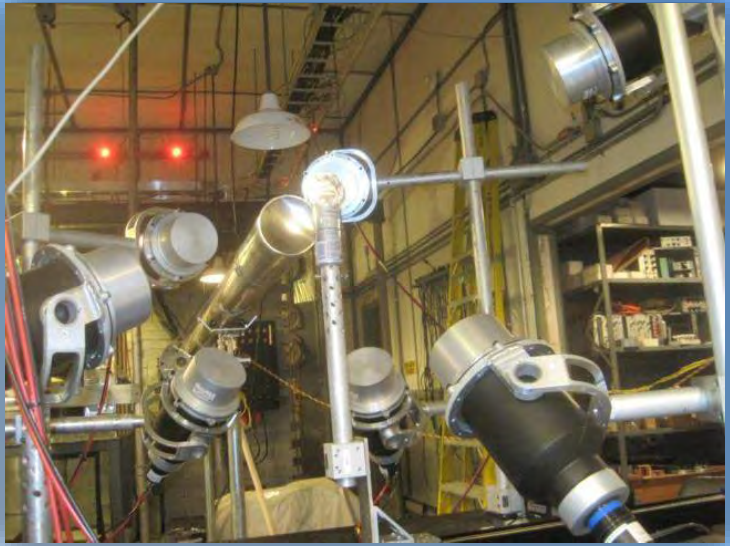


- 100m flight path
- Used low Hf (less than 100 ppm) Zr metal
- ENDF/B 6.8 seems like a better fit for E<16 MeV
- New partially resolved structure below 2.0 MeV
- Data can be used to improve the unresolved resonance region evaluation



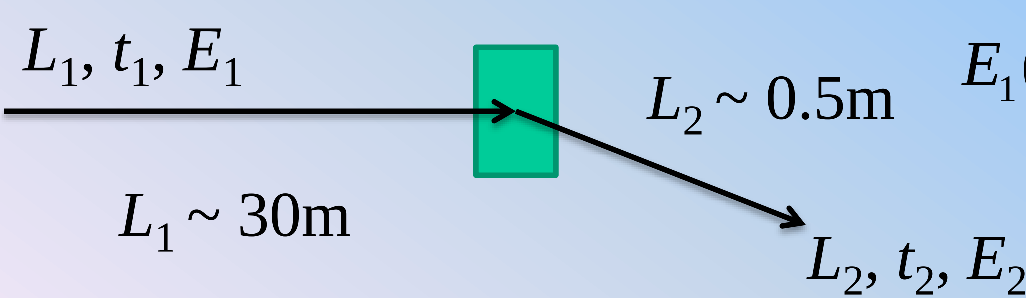
Fast Neutron Scattering

Quasi-differential neutron scattering and angular distributions.



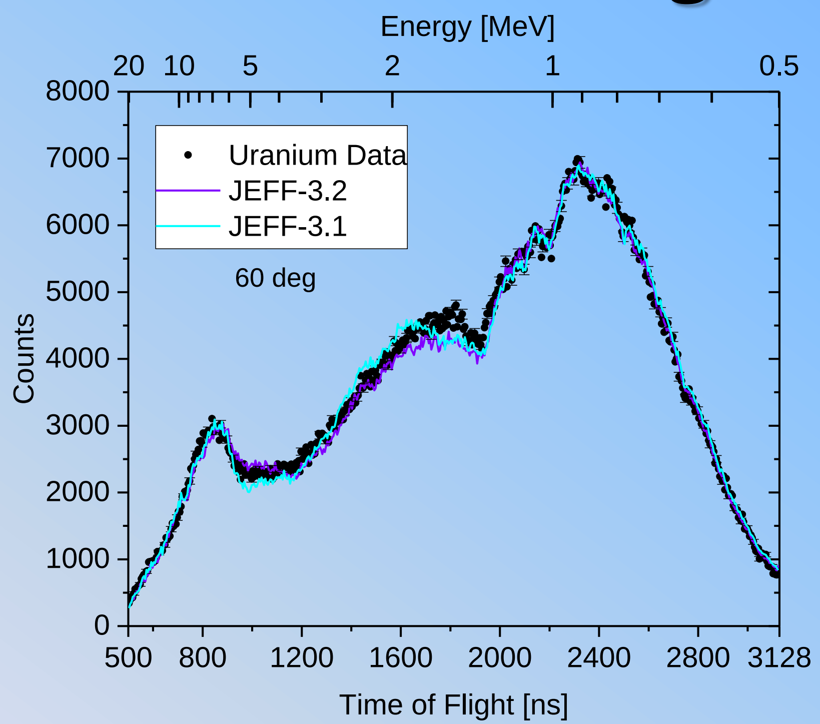
TOF Scattering Measurement

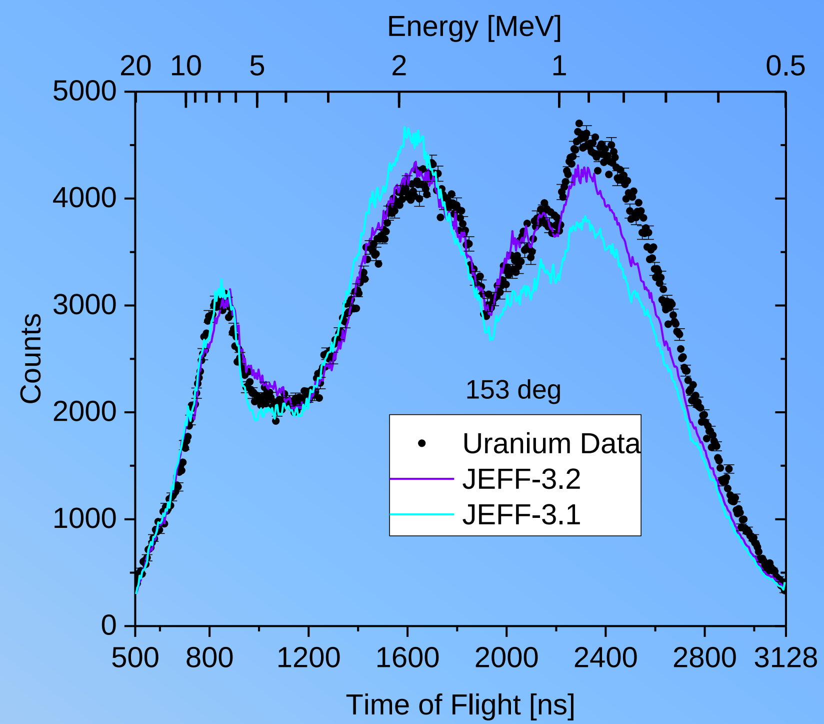
- Measure TOF: $t = t_1 + t_2$; where t_1 » t_2
- All scattering events: $E_2 < E_1$
- For elastic scattering with A » 1: $E_1 \sim E_2$
- Assuming $L = L_1 + L_2$ than total TOF, t, can be used to calculate the incident neutron energy, $E_1(t)$



$$E_1(t) \approx m_n c^2 \cdot \left(\frac{1}{\sqrt{1 - \left(\frac{L}{c \cdot t} \right)^2}} - 1 \right)$$

^{238}U Scattering Measurement - JEFF 3.2





Library	FOM
JEFF-3.1	3.0
JEFF-3.2	2.8

Library	FOM
JEFF-3.1	20.4
JEFF-3.2	7.9

- Significant improvement in JEFF3.2

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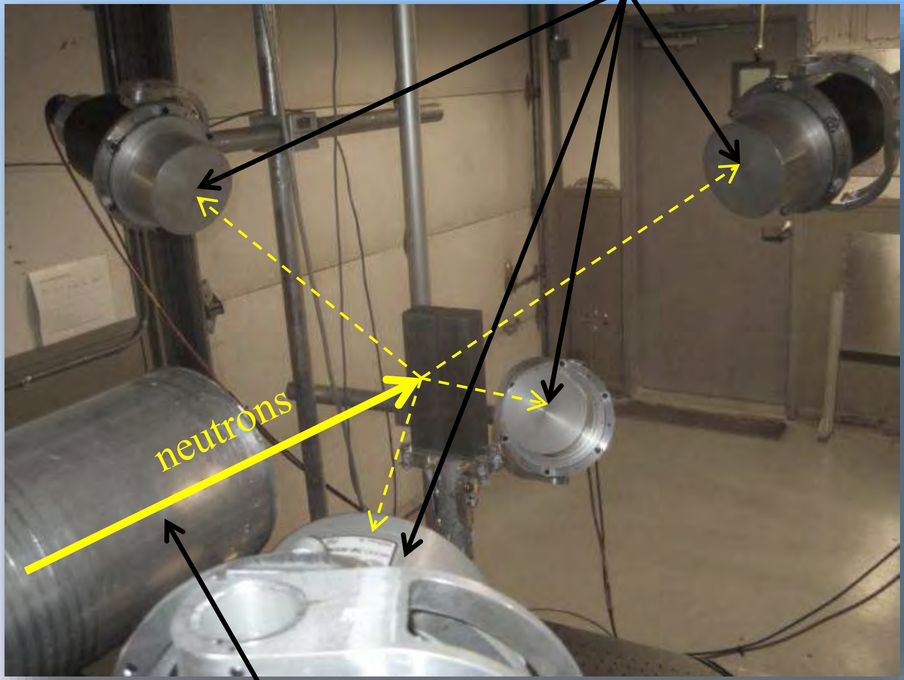
Fe Scattering Measurement - Setup

EJ-301 Liquid Scintillator Neutron Detectors



Evacuated Flight Tube

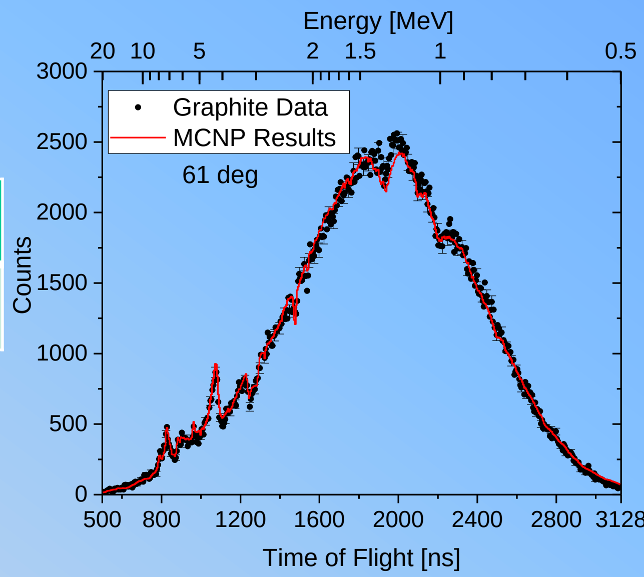
- Fe Sample
- Dimensions 77.0 x 152.6 x 32.2 mm

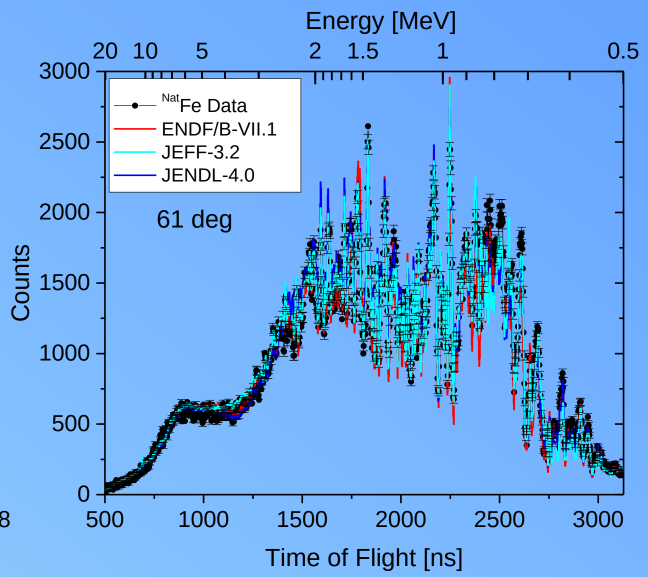
The neutron beam size is smaller than the sample.

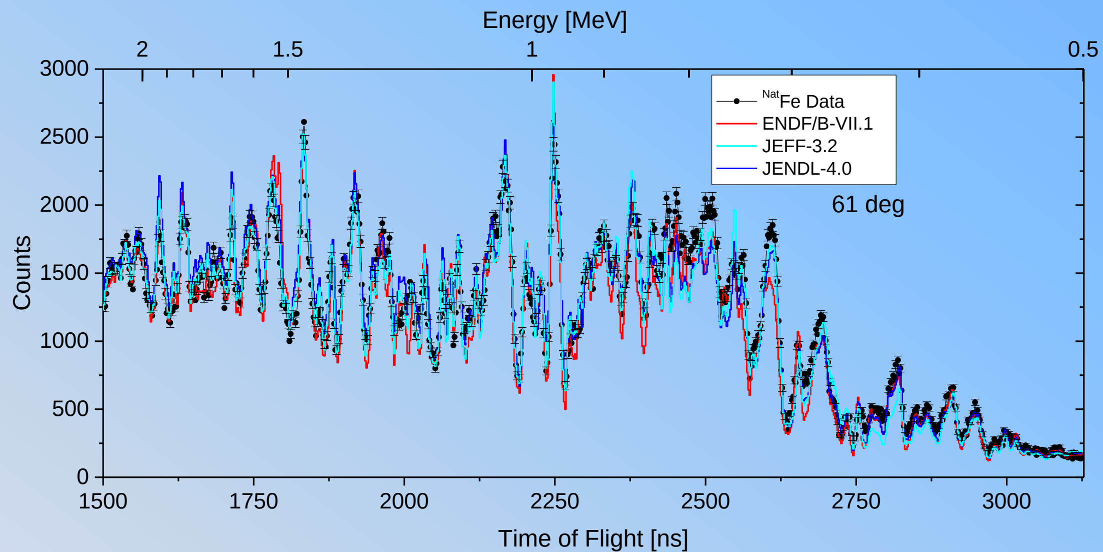
^{nat}Fe Scattering - 61°

Reference	FOM
Graphite	1.3

Library	FOM
ENDF/B-VII.1	9.5
JEFF-3.2	9.5
JENDL-4.0	8.4

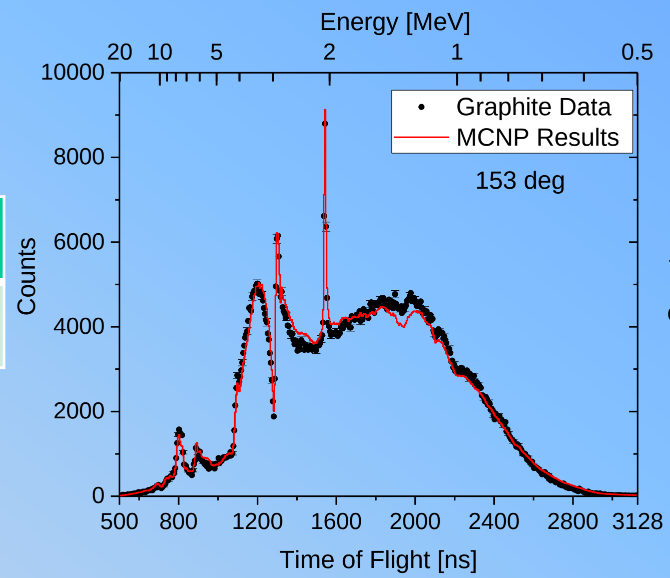


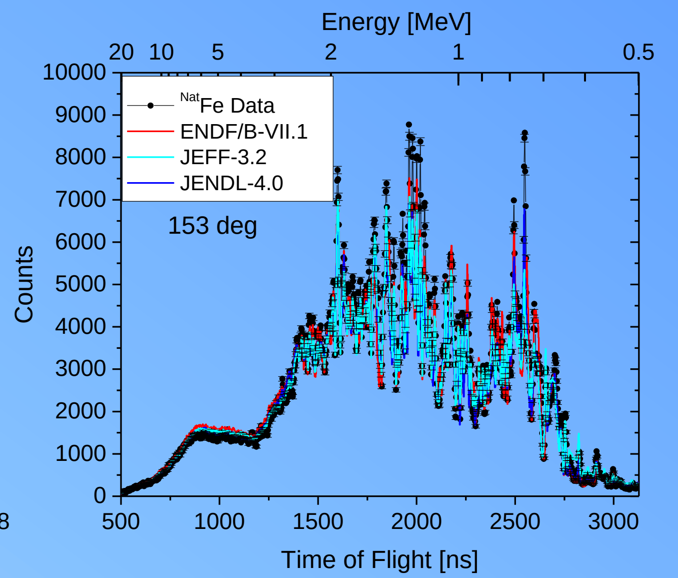




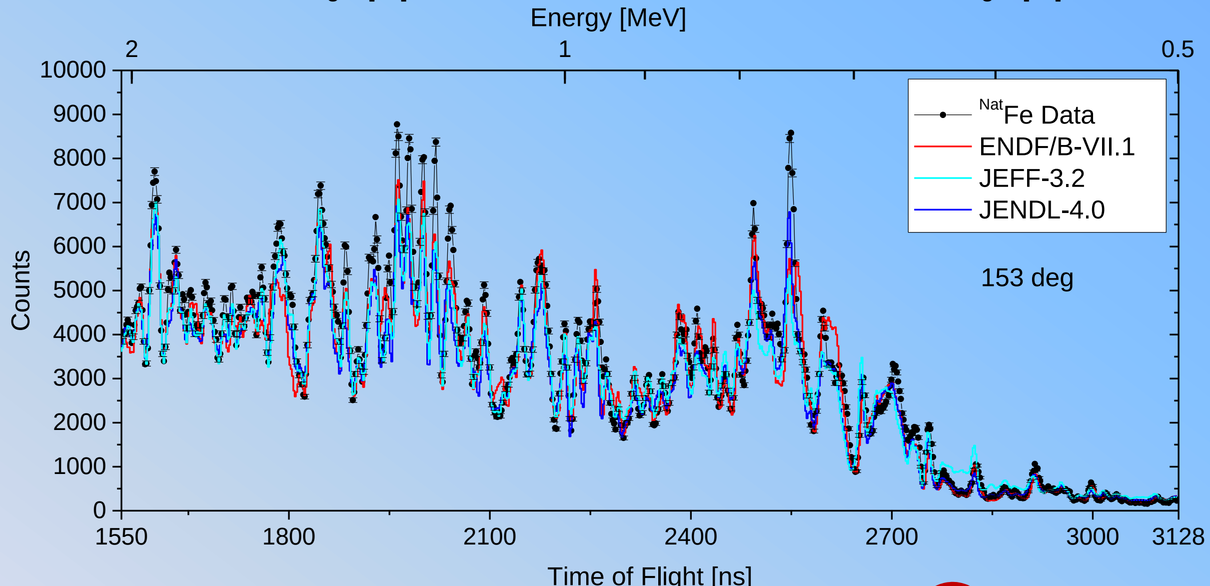
^{nat}Fe Scattering - 153°

Reference	FOM
Graphite	4.9





Library	FOM
ENDF/B-VII.1	25.9
JEFF-3.2	39.8
JENDL-4.0	23.4



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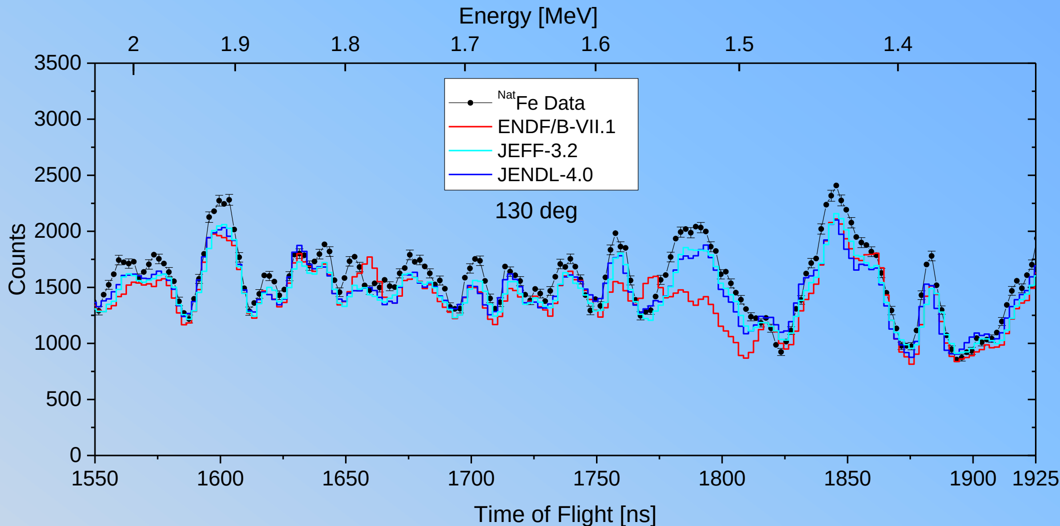
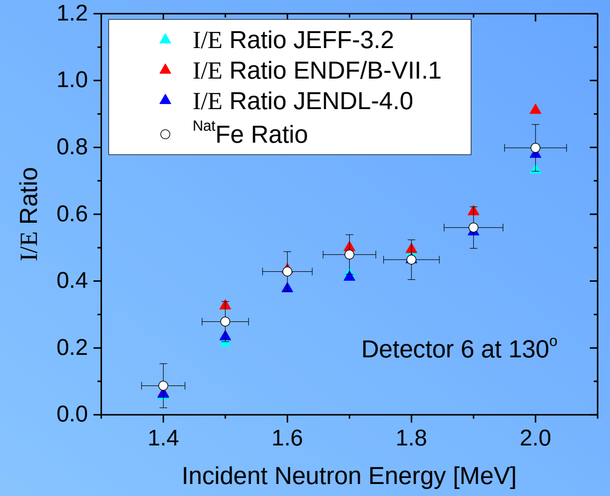
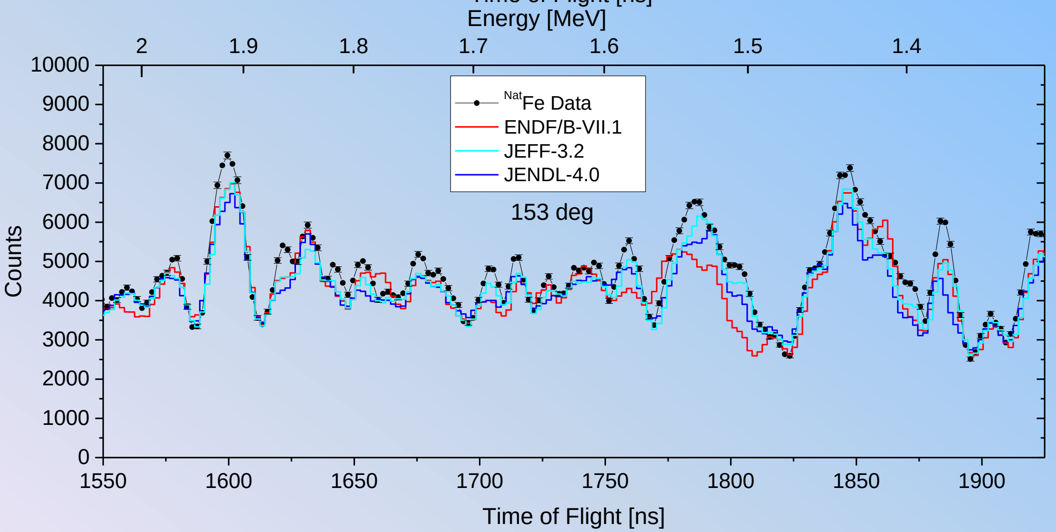
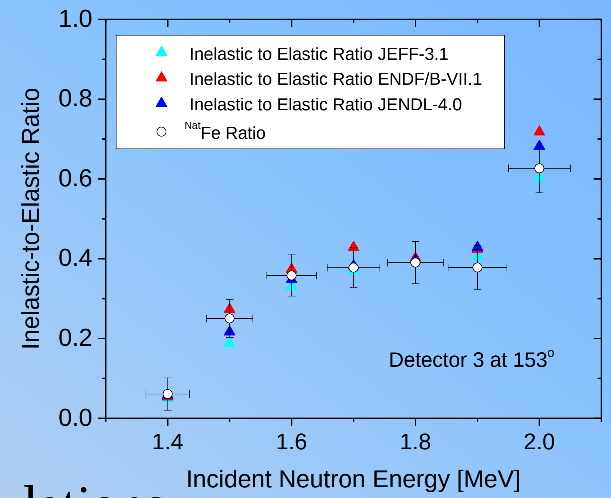
Inelastic to Elastic Ratio





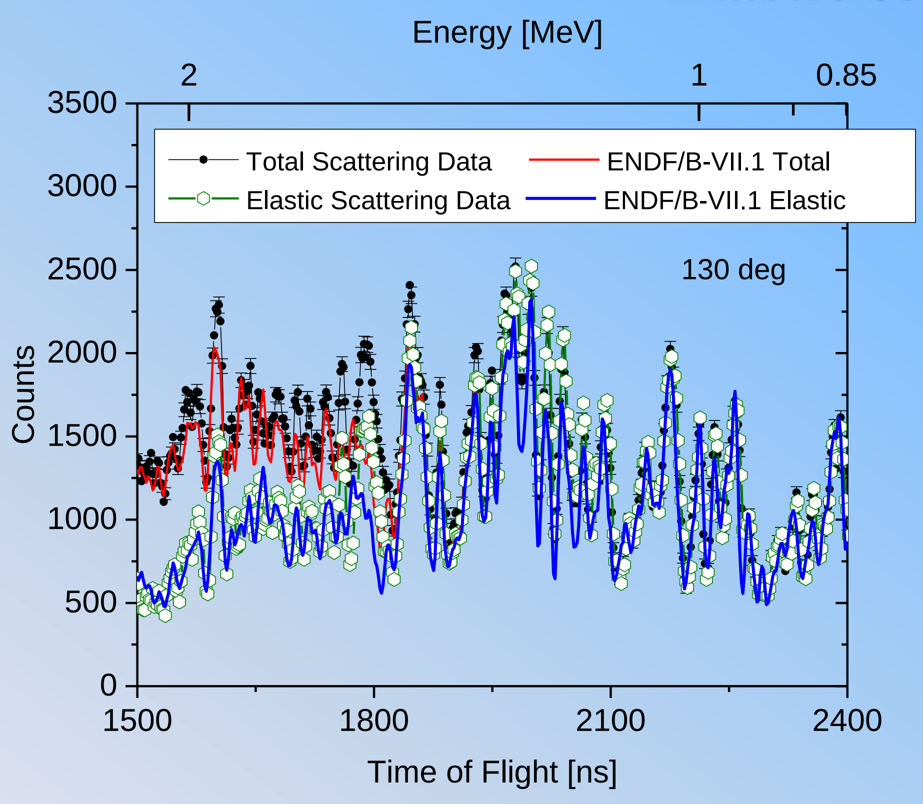


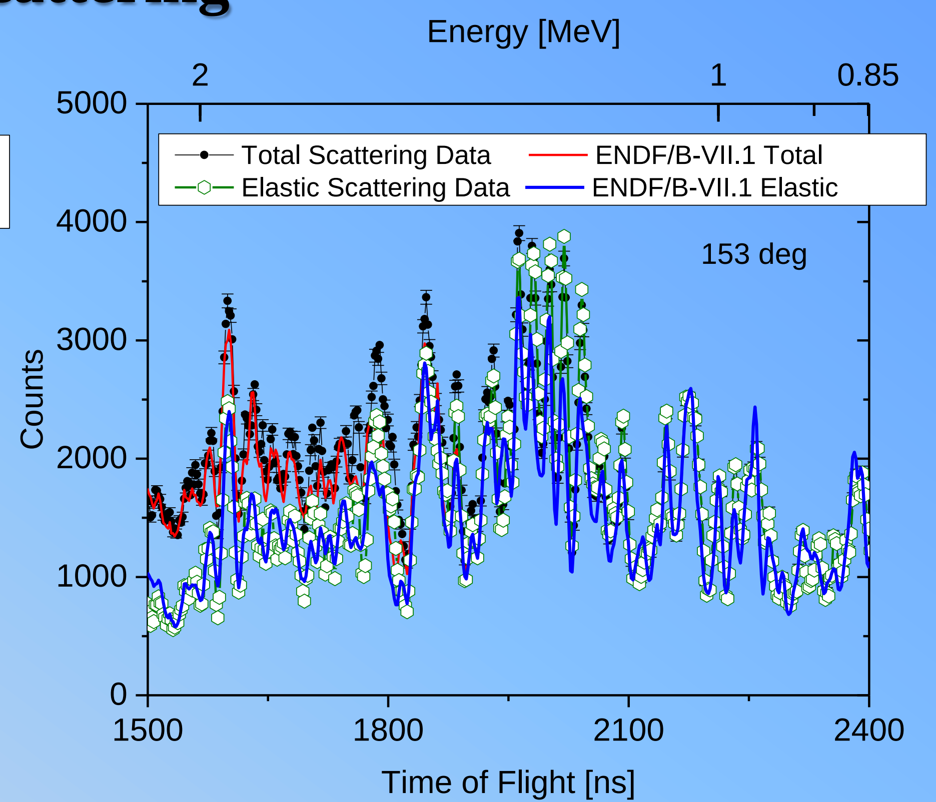


- Multiple scattering effects included in MCNP simulations
- Statistical and systematic uncertainties included in analysis

Comparing Experiments and Simulation

Elastic scattering





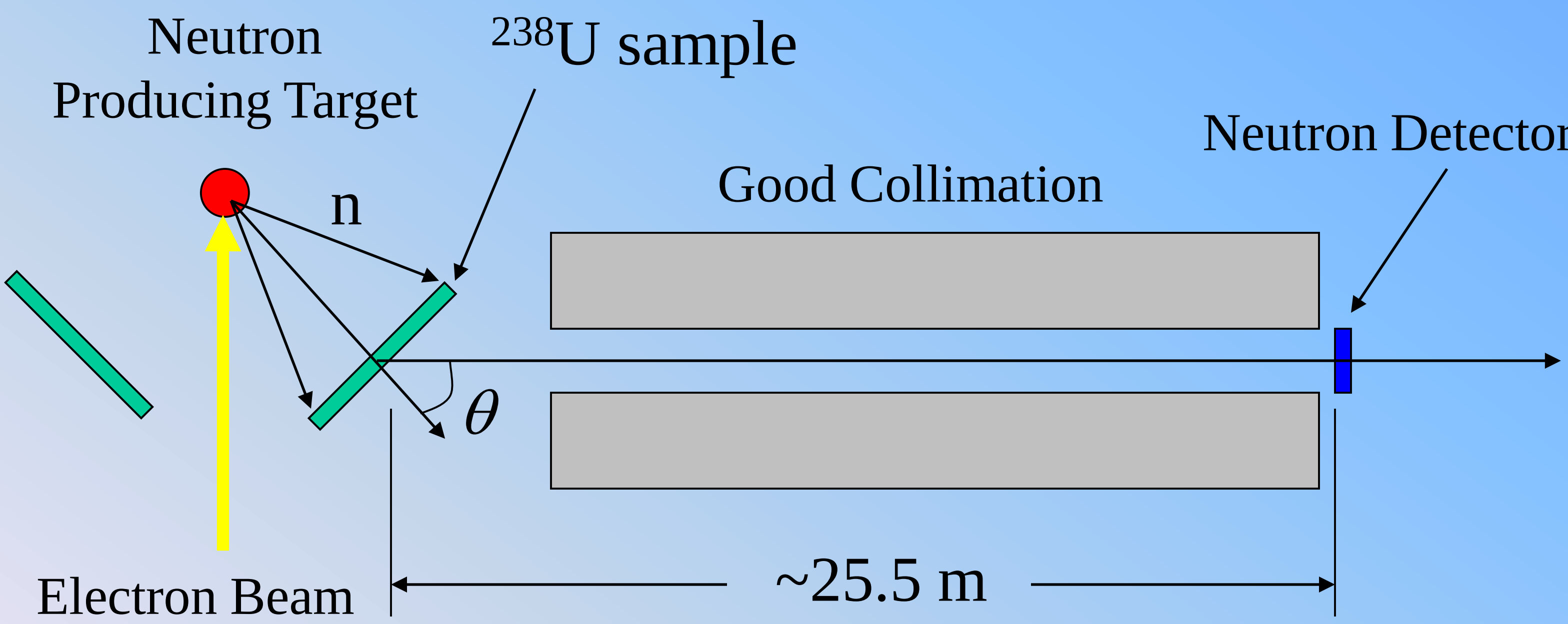
- Experimental elastic scattering was inferred from 0.5 to 2.0 MeV
  - The experimental data is reasonably represented by a simulation with ENDF/B-VII.1
- Collaborating with ORNL to improve new ^{56}Fe evaluation

Resonance Scattering

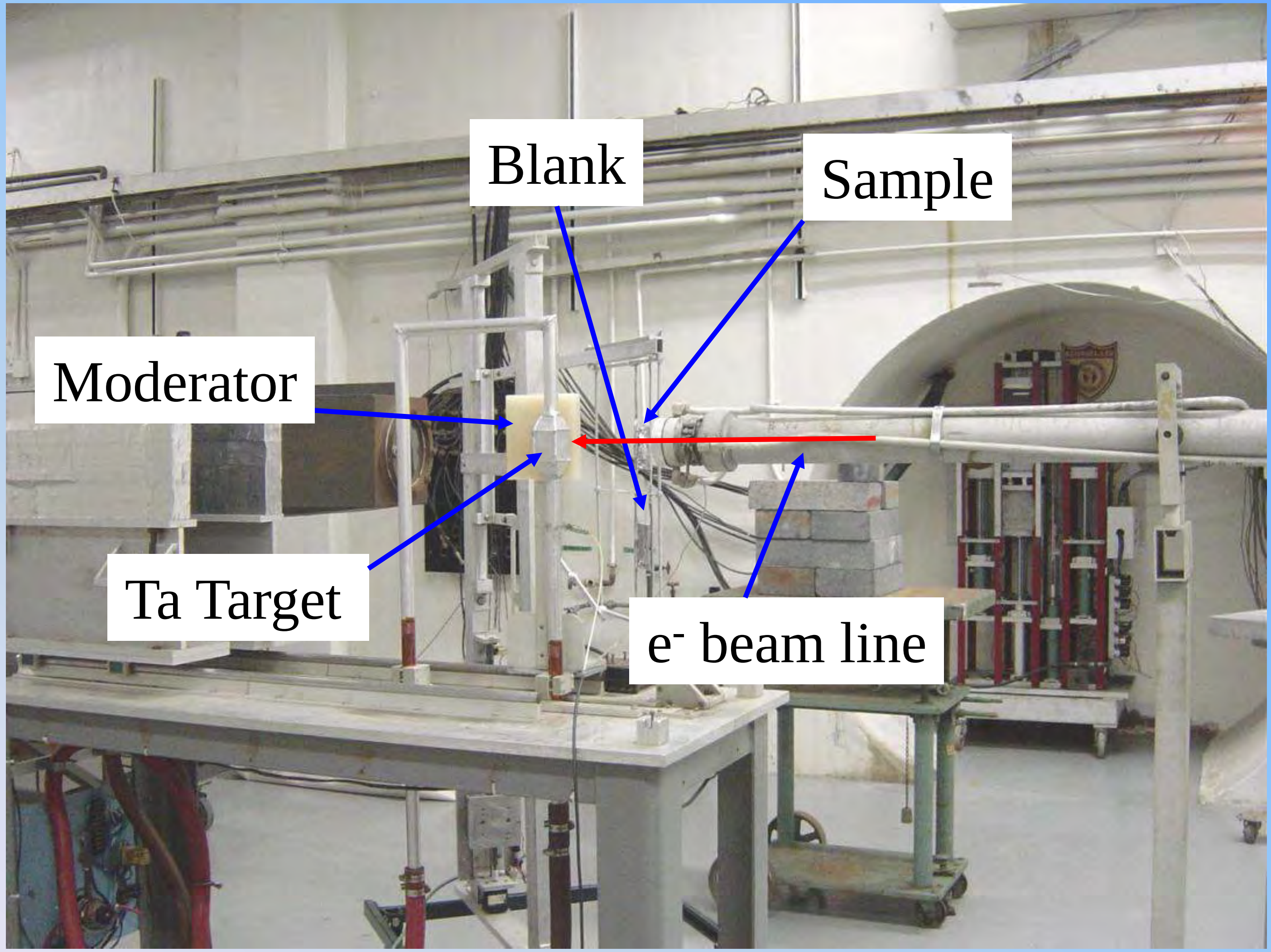
Example of an experiment for testing the physics models of Monte Carlo codes

Resonance Scattering Experiment

- Motivation – Provide a benchmark to the model developed by Dagan et al.
  - Poor approximation of the scattering kernel when the cross section is energy dependent.
- Use the Time-Of-Flight (TOF) method
  - The TOF will correspond to the scattered neutron energy
  - Scattering in forward and backward scattering angles can be measured



Resonance Scattering- Experimental Setup



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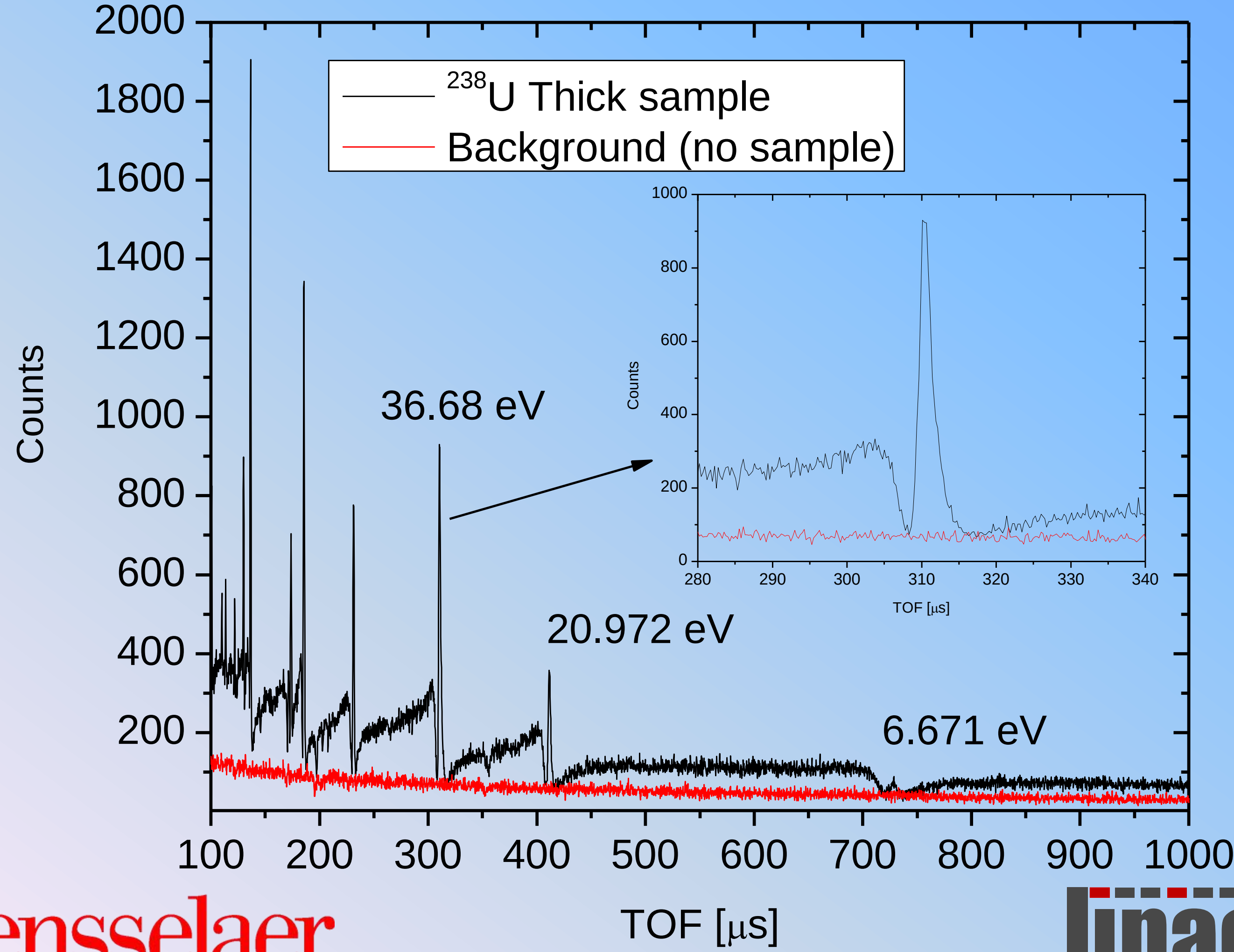
Resonance Scattering-Measured Data

- Thick Sample time-of flight spectrum forwards scattering



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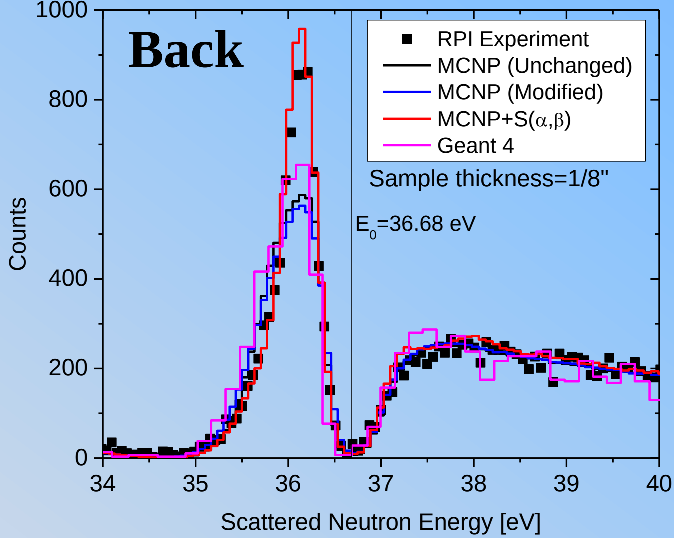
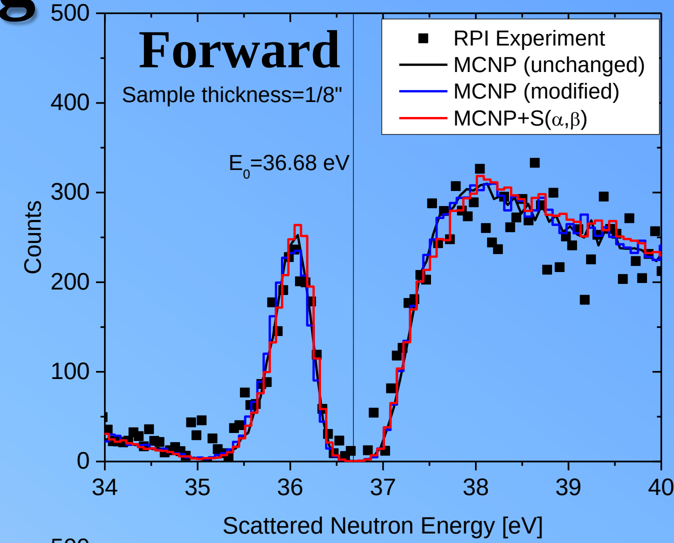
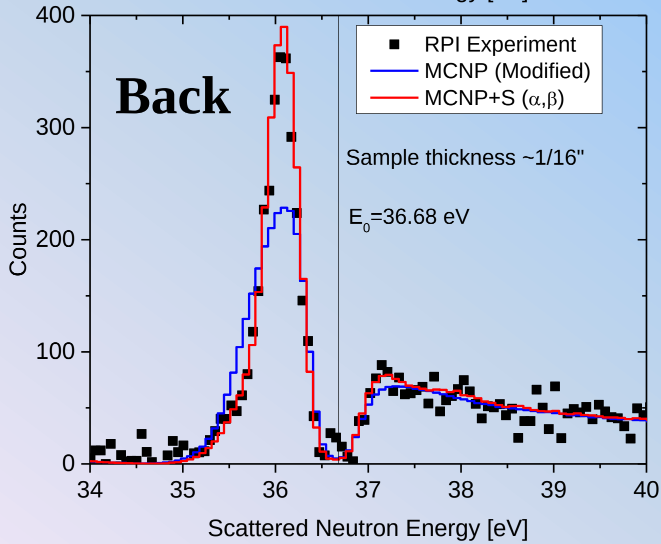
Resonance Scattering - Results for ^{238}U Scattering

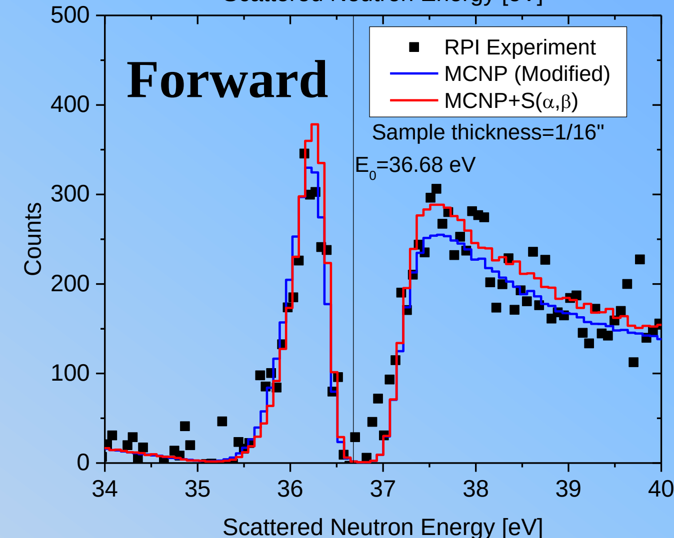


Thick Sample





Thin Sample



In 2009 all MC codes had this problem
Today some still do

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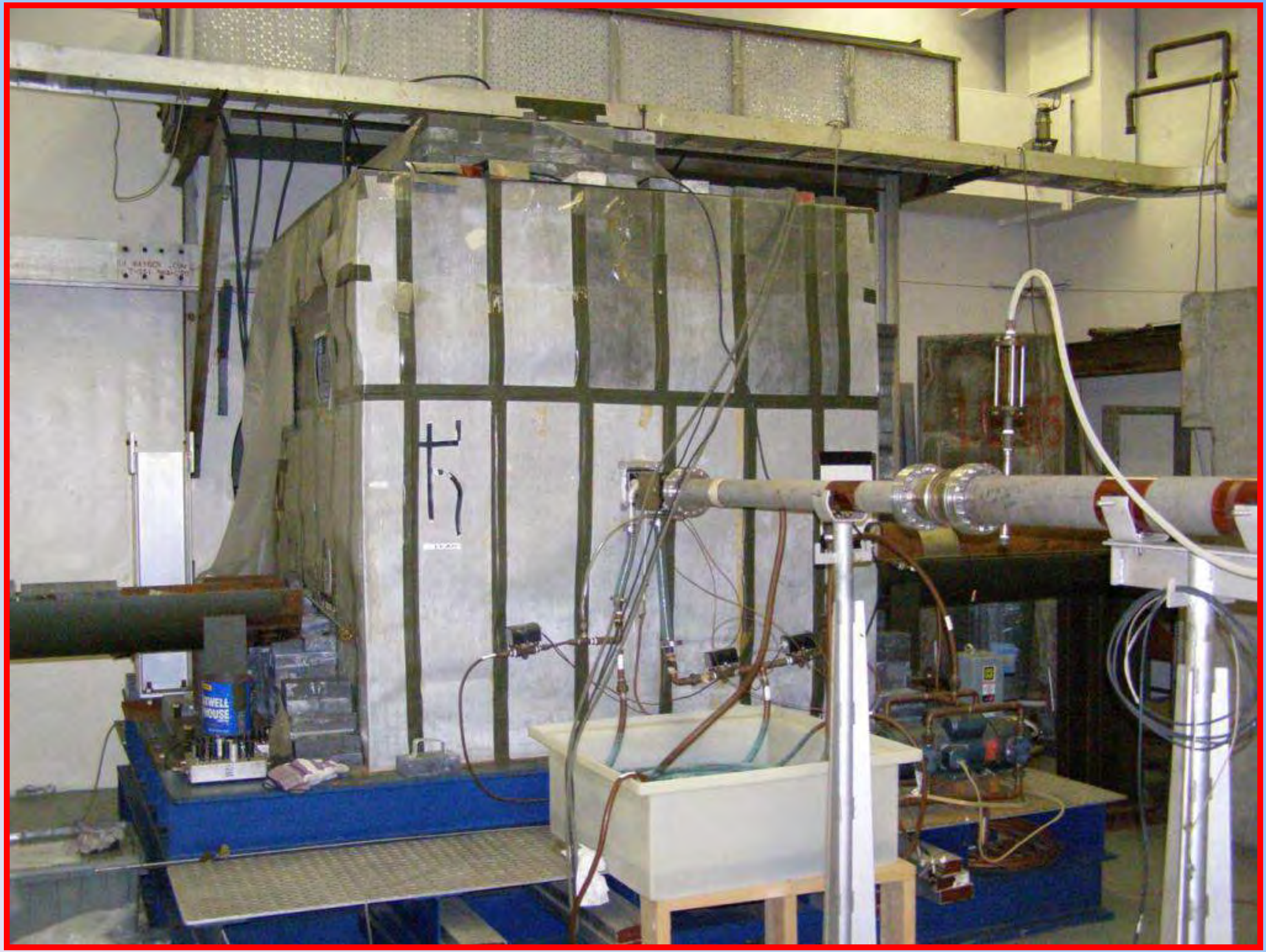
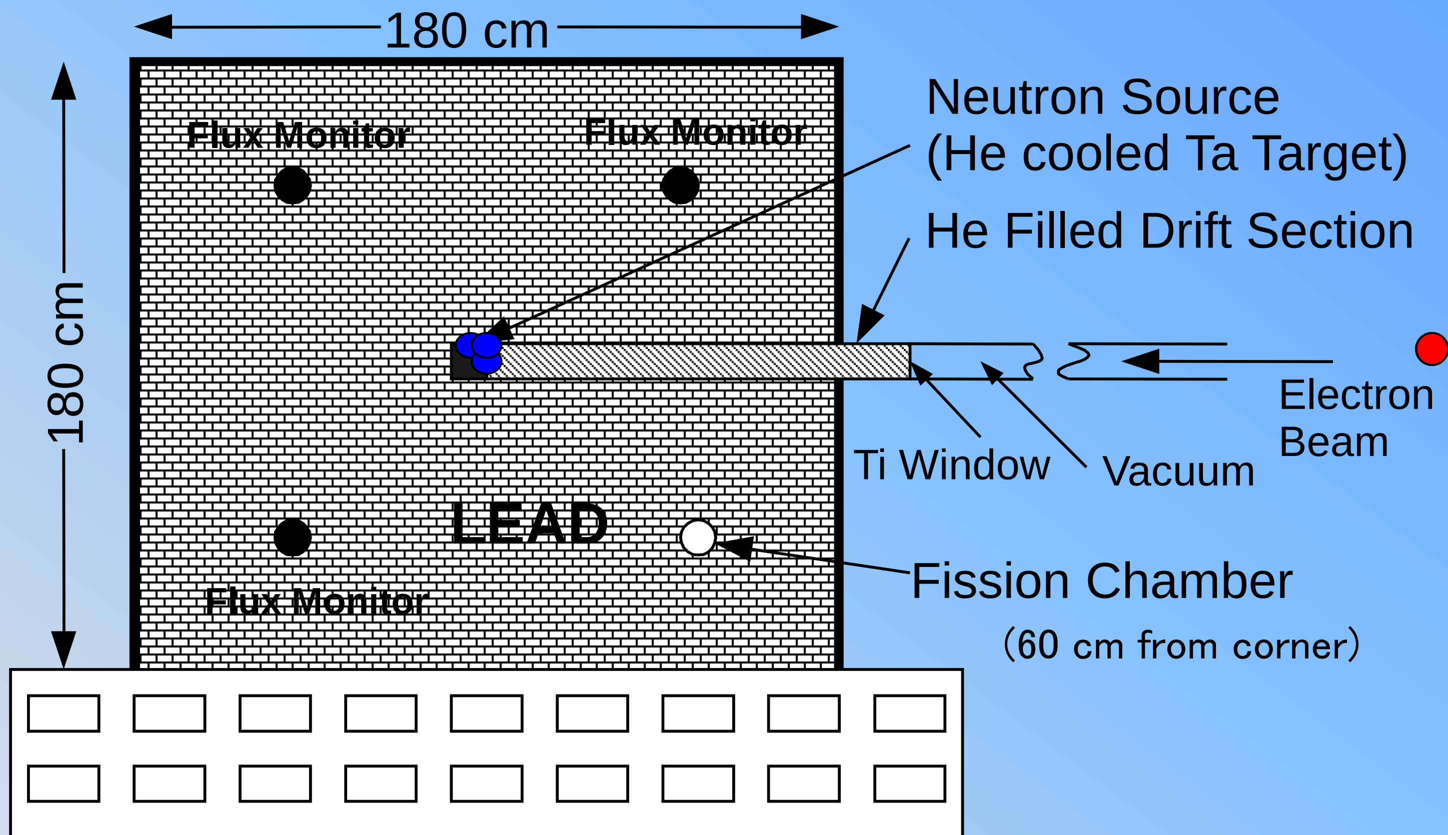
Lead Slowing Down Spectrometer



Lead Slowing-down Spectrometer at RPI

- Tantalum target in the center produces neutrons.
- Neutrons scatter elastically with the Pb.
- Neutrons can pass through the same position several times.
- About 10^3-10^4 times higher flux than an equivalent flight path TOF experiment (5.6m).

67 tons of Pb



Crossed I beam + Li_2Co_3

Fission Fragment Kinematics

- **Objectives**
  - Simultaneous measurement of the fission cross section and fission fragment mass and energy distributions of small samples (~nanograms).
- **Method**
  - Use the RPI lead slowing down spectrometer and a double gridded fission chamber.
  - Samples are deposited on very thin backing (~250 nm)

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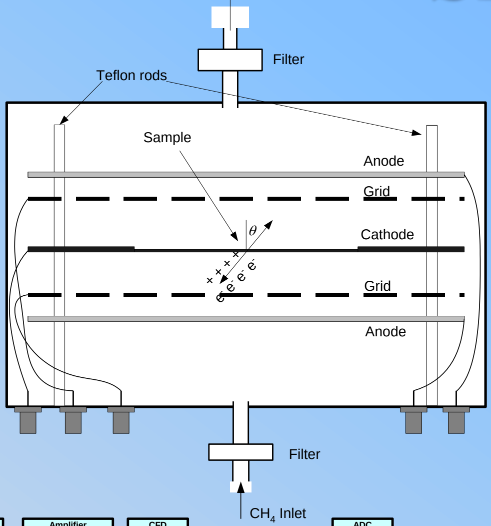
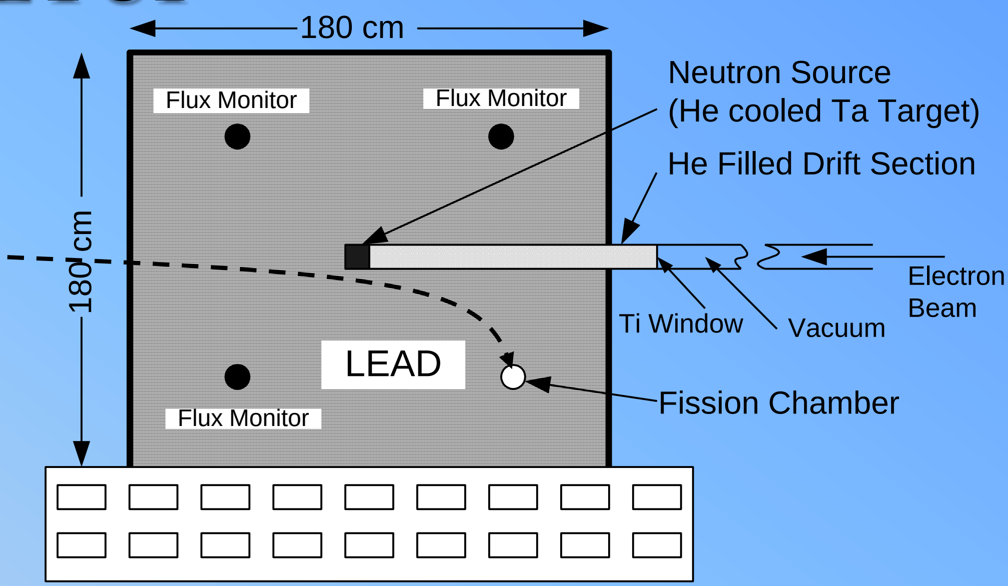
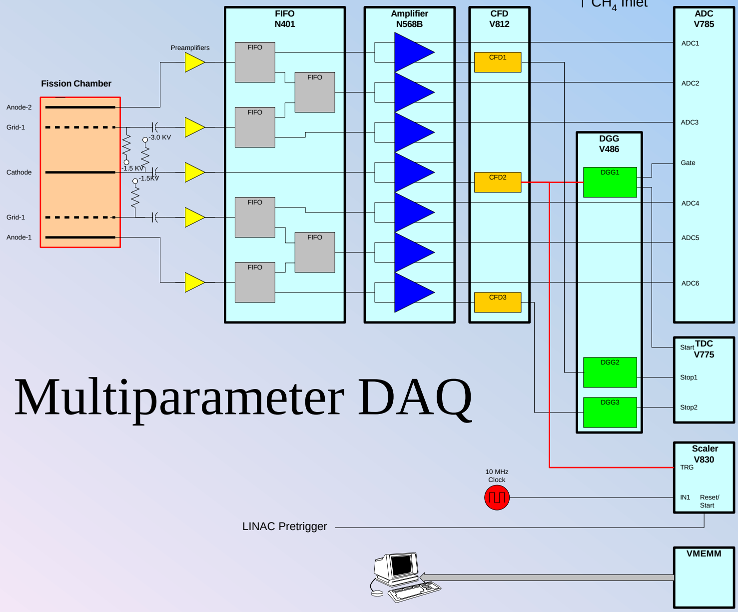
SETUP

Double Gridded Fission Chamber





Crossed I beam + Li_2Co_3



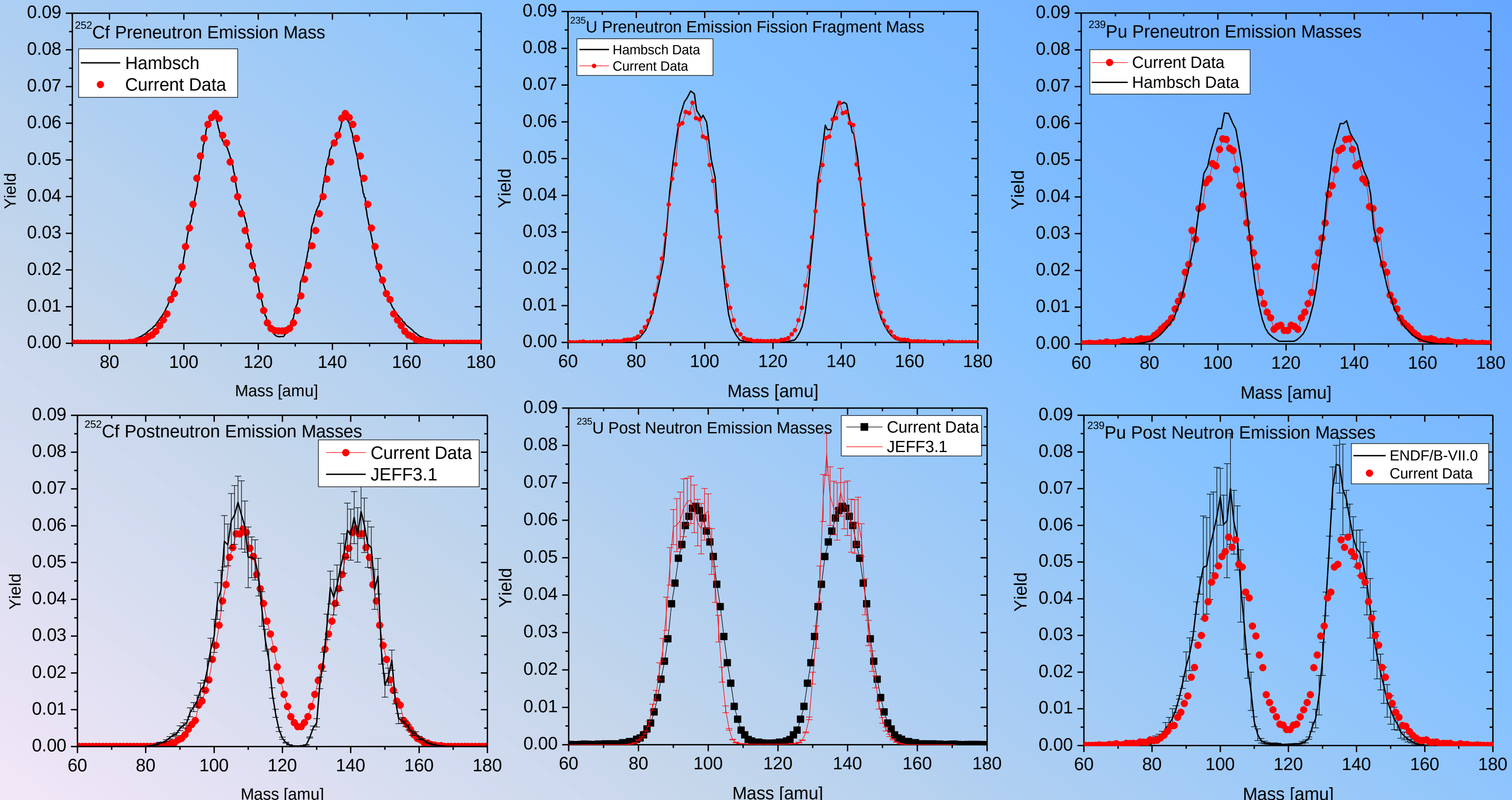
Multiparameter DAQ

Collaboration with LANL

- Fission cross sections.
- (n,α), (n,p) measurements on small samples.

Results – Fission Fragment Mass distribution E_n<0.1 eV

^{252}Cf ^{235}U ^{239}Pu



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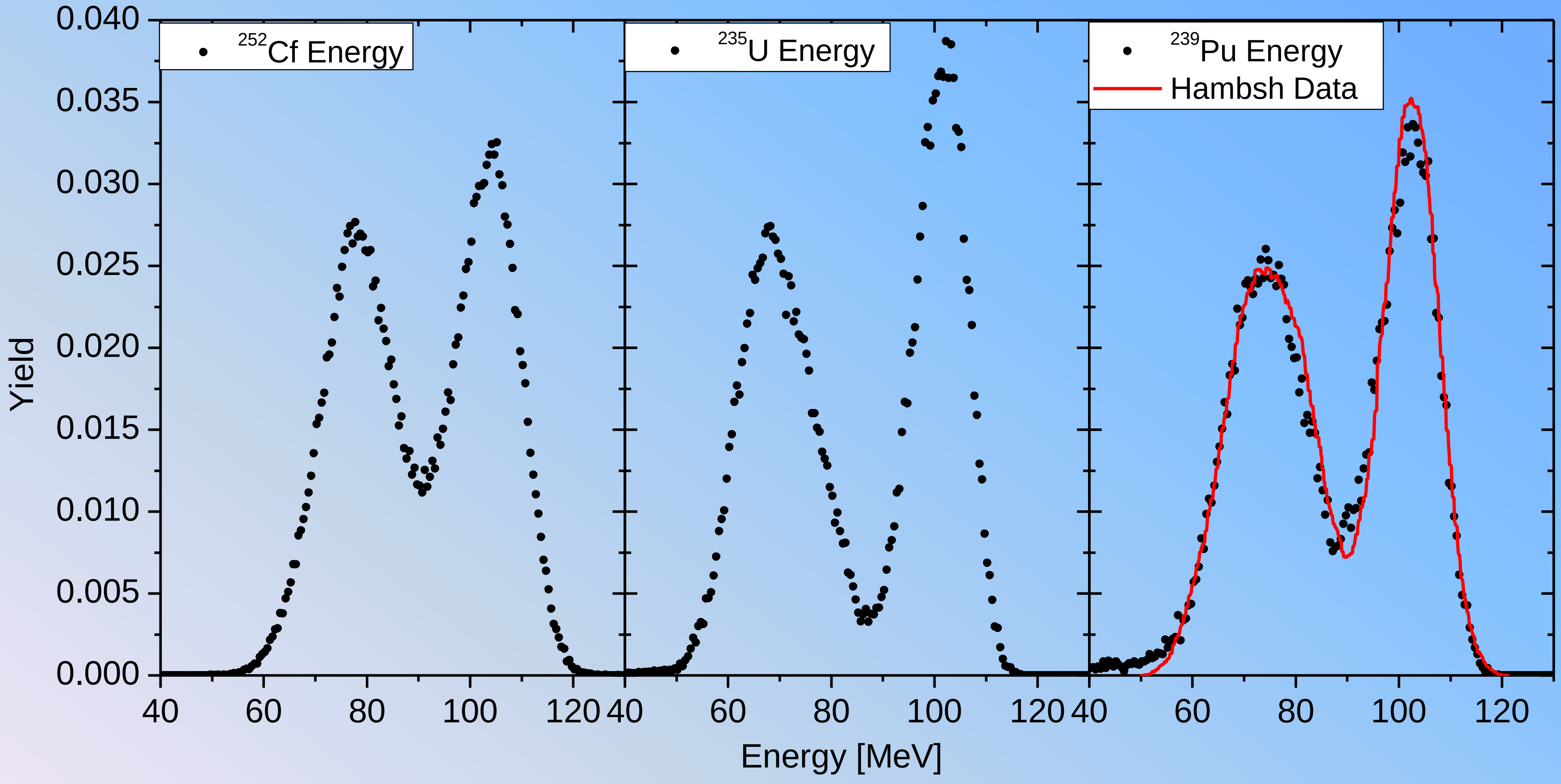
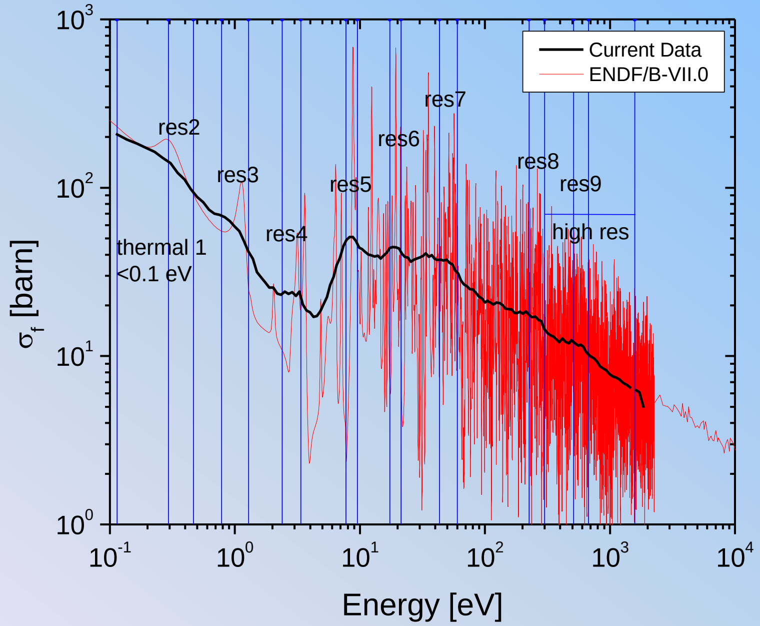
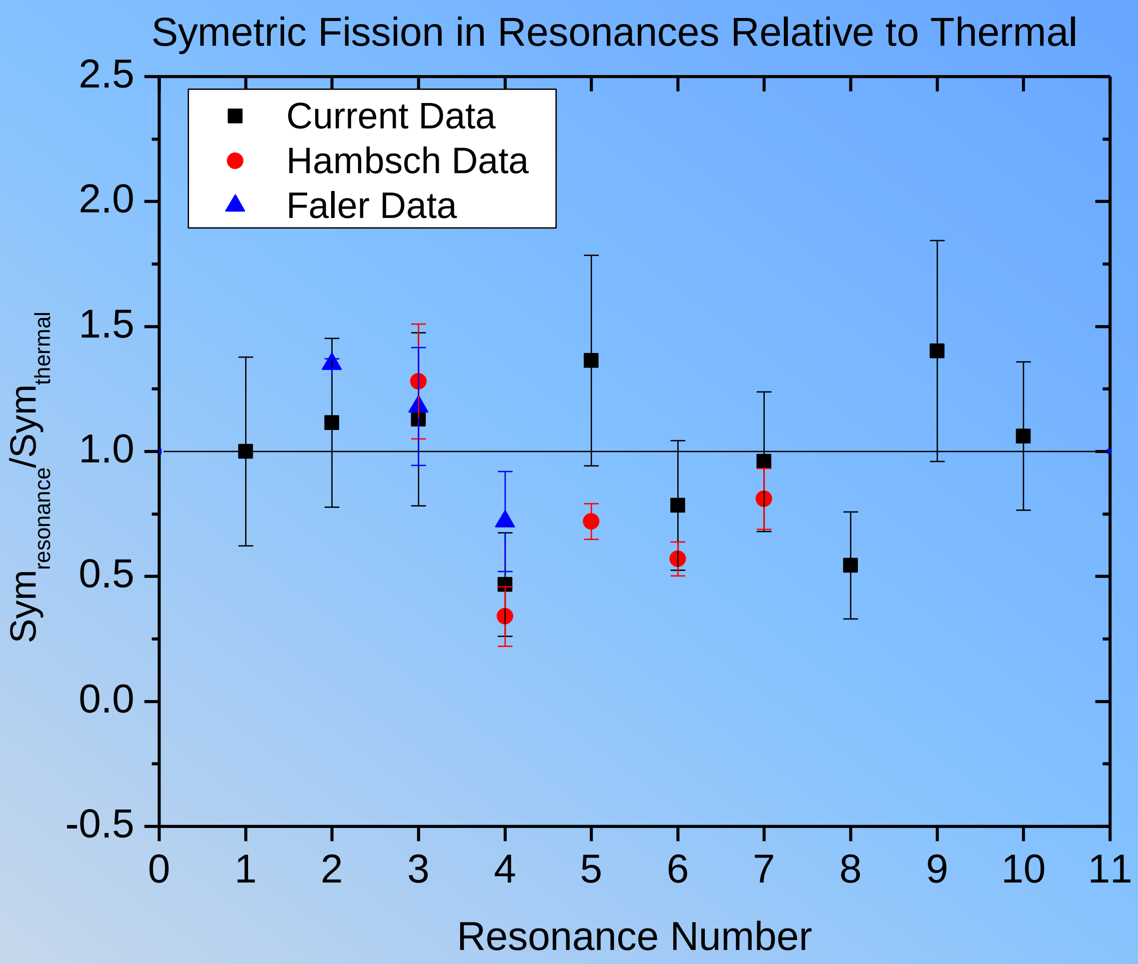
Results – Fission Fragment Energy Distribution E_n<0.1 eV



Fission symmetry in resonance clusters





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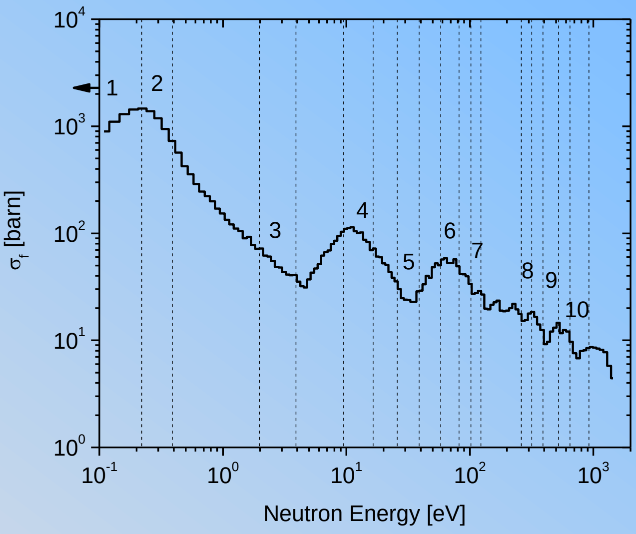
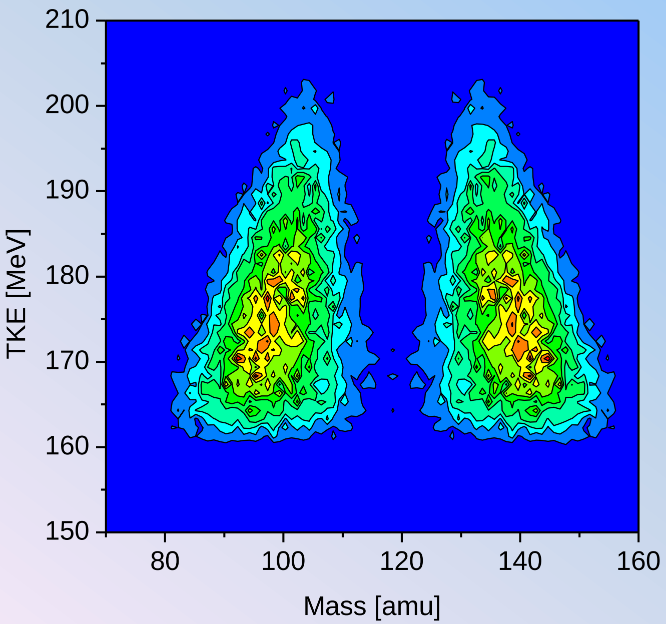
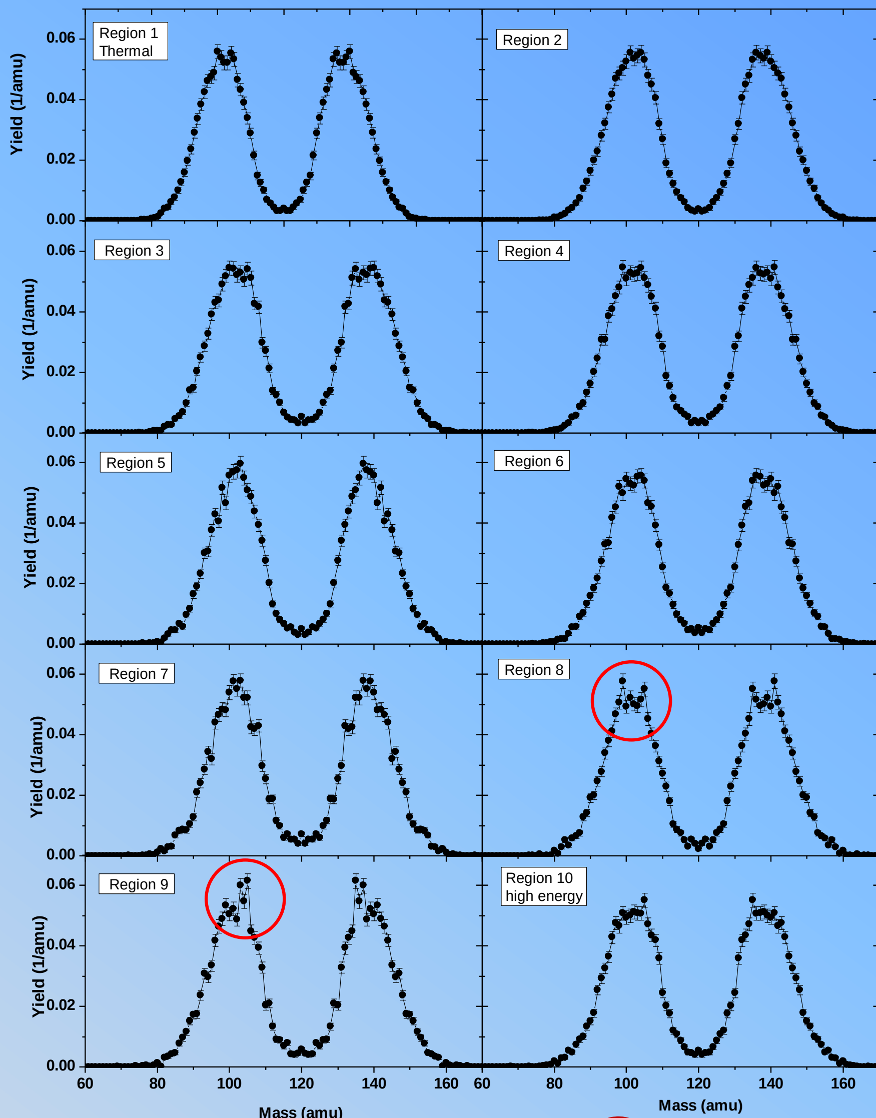
^{239}Pu - Results







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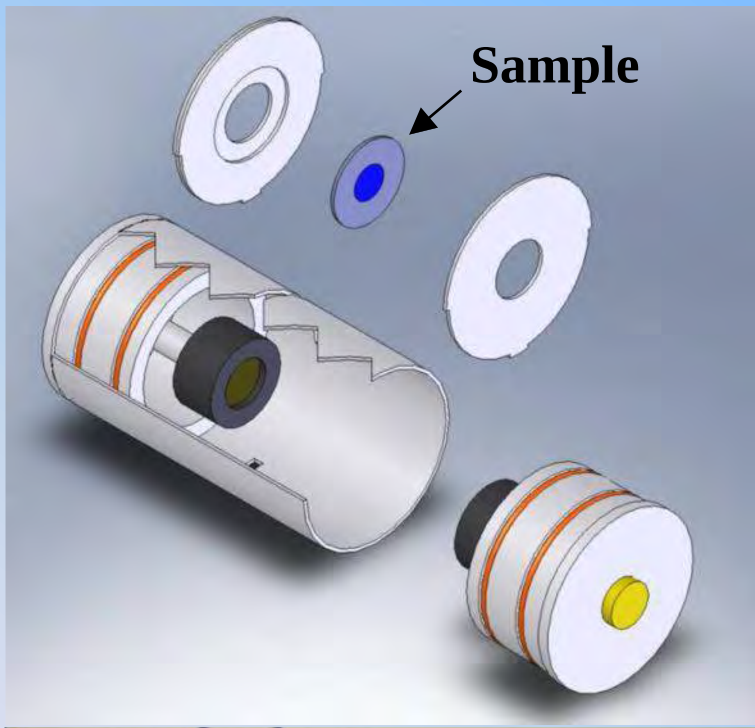
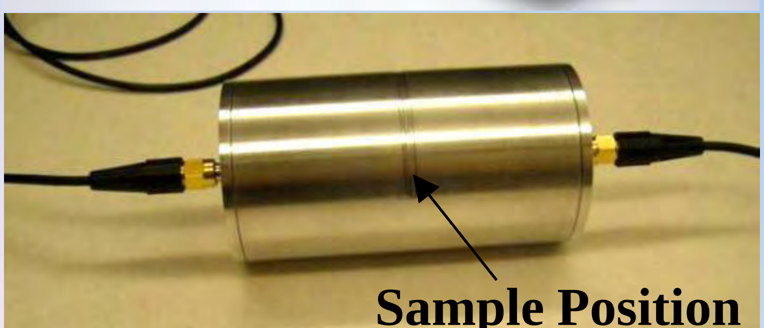
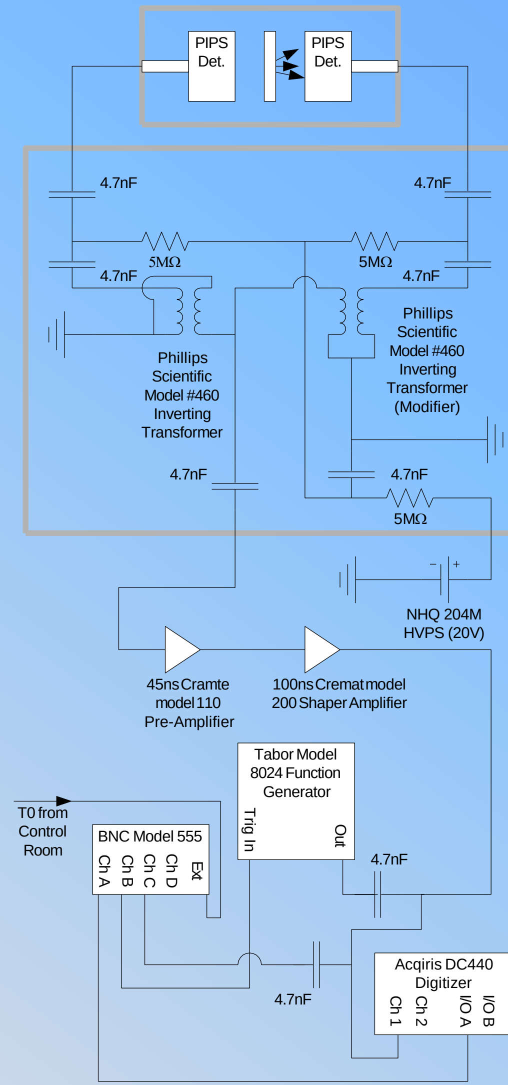
(n,α) cross section measurements

Compensated PIPS Detector







- Gamma discrimination by recording the gamma spectra on two face to face detectors
- Digital DAQ collects a bipolar signal
- Correct for background by subtracting the bare detector signal from the sample detector on an event by event basis

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(n,α) and (n,p) measurement results

- Measurement of (n,α) cross section of ^{147,149}Sm
- Demonstrate the ability to measure micro barn cross sections with the LSDS

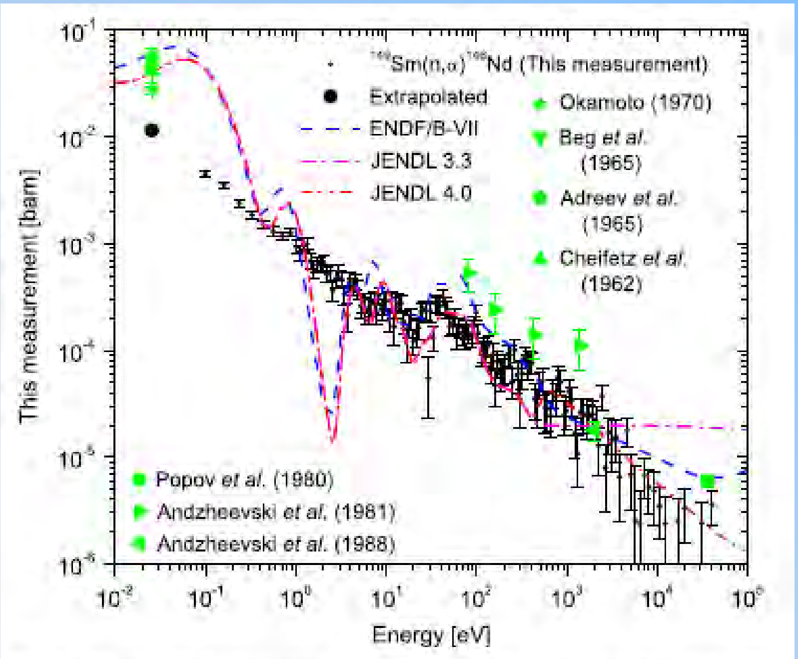


Fig. 9. Measured ^{149}Sm(*n*,*α*) cross section compared to previous measurements [17,19–24] and evaluations [18] broadened by the method given by Danon [13].

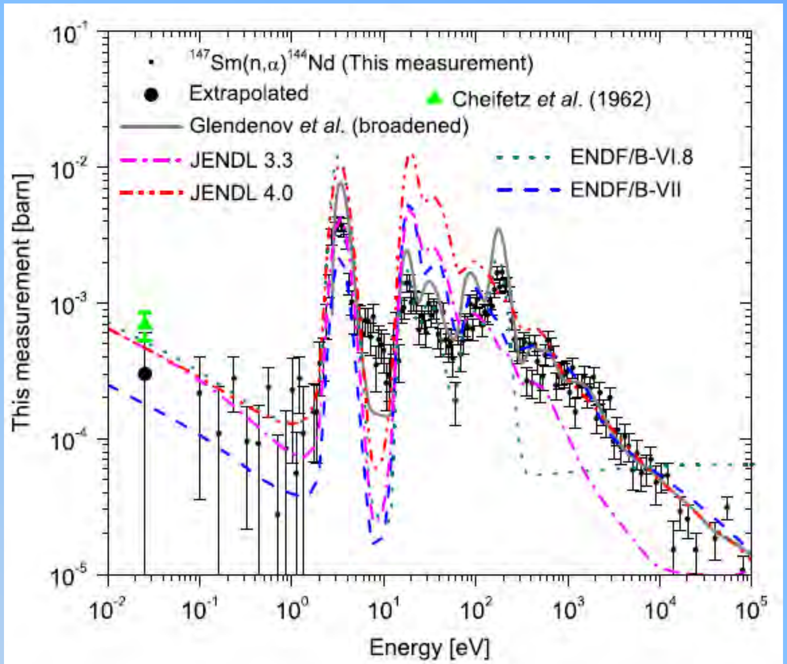
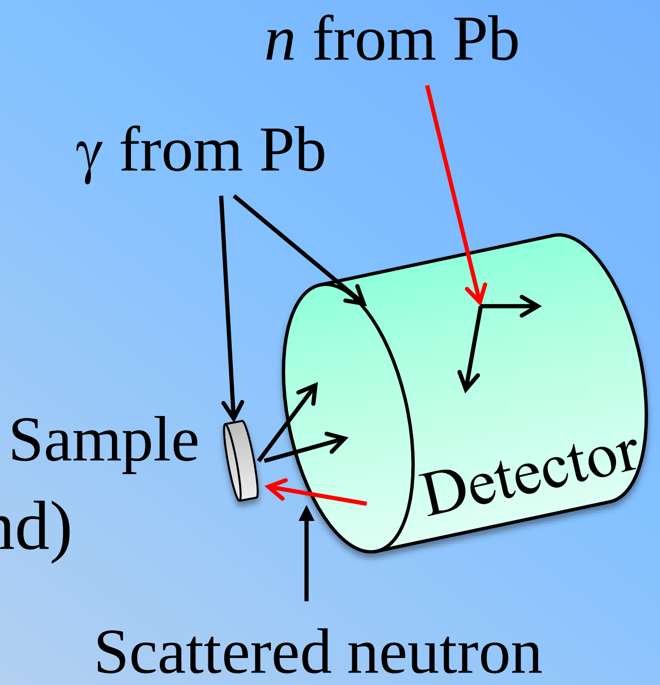


Fig. 8. Measured ^{147}Sm(*n*,*α*) cross section compared to previous measurements [7,17] and evaluations [18] broadened by the method given by Danon [13].

J.T. Thompson, T. Kelley, E. Blain, R.C. Haight, J.M. O'Donnell, Y. Danon, “Measurement of (n,α) reactions on ^{147}Sm and ^{149}Sm using a lead slowing-down spectrometer”, Nuc. Inst. and Meth. A, Vol. 673, pp. 16-21, May (2012)

Capture measurements with the LSDS

- Use a Lead Slowing Down Spectrometer to measure the capture rate of samples of small mass or small cross section
  - Detect γ from capture
- Criteria for a γ detector
  - Low n-capture cross section
  - Low n-scattering cross section
  - High γ detection efficiency
  - Small detector (reduce background)
  - Fast recovery from gamma flash



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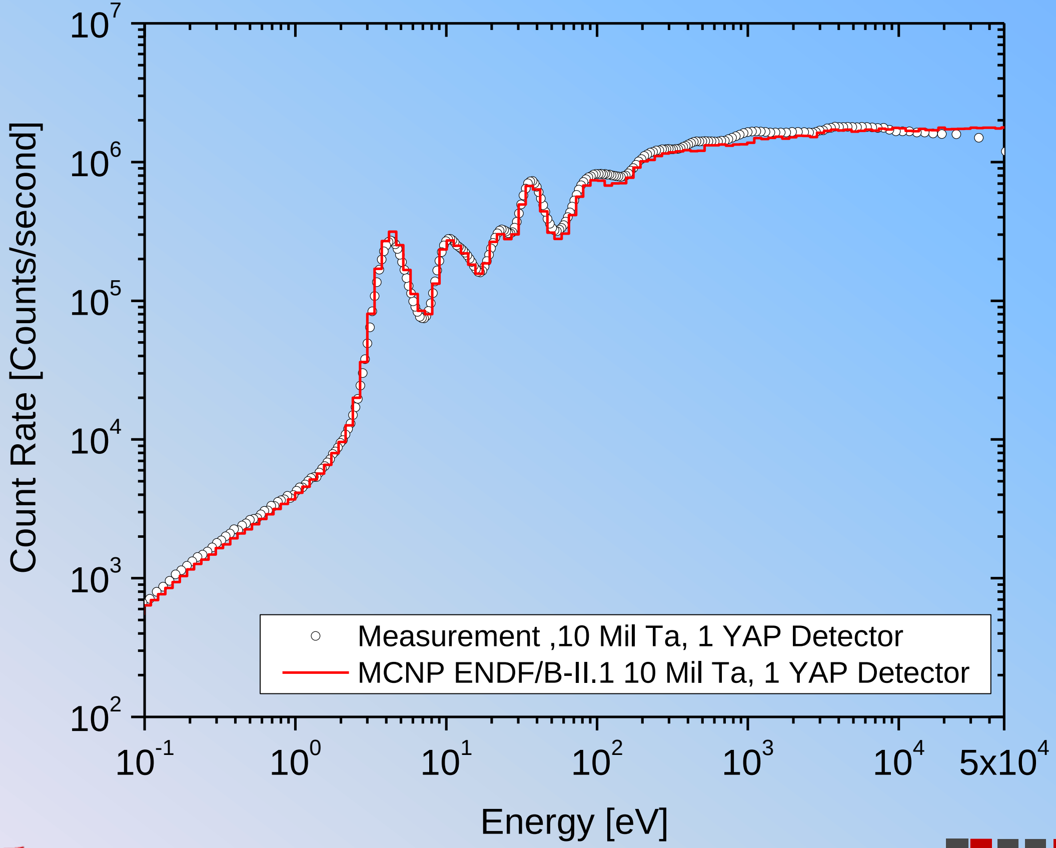
Ta capture rate

- 2mm YAP Detector, 10 Mil Ta Sample
  - The measurement extends to ~50 keV
  - Good agreement with the simulations
  - Data collection time was about 20 minutes



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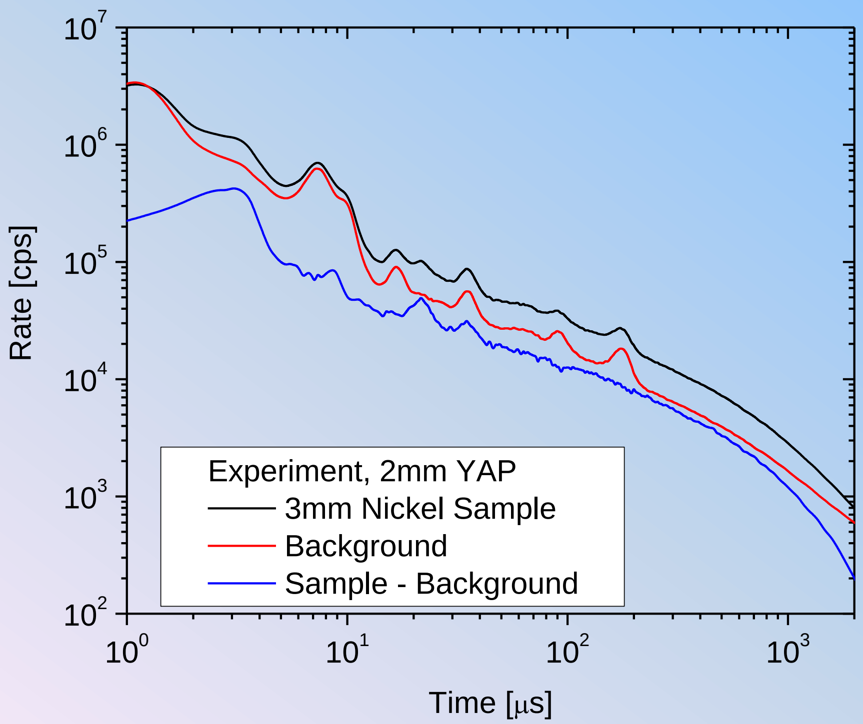
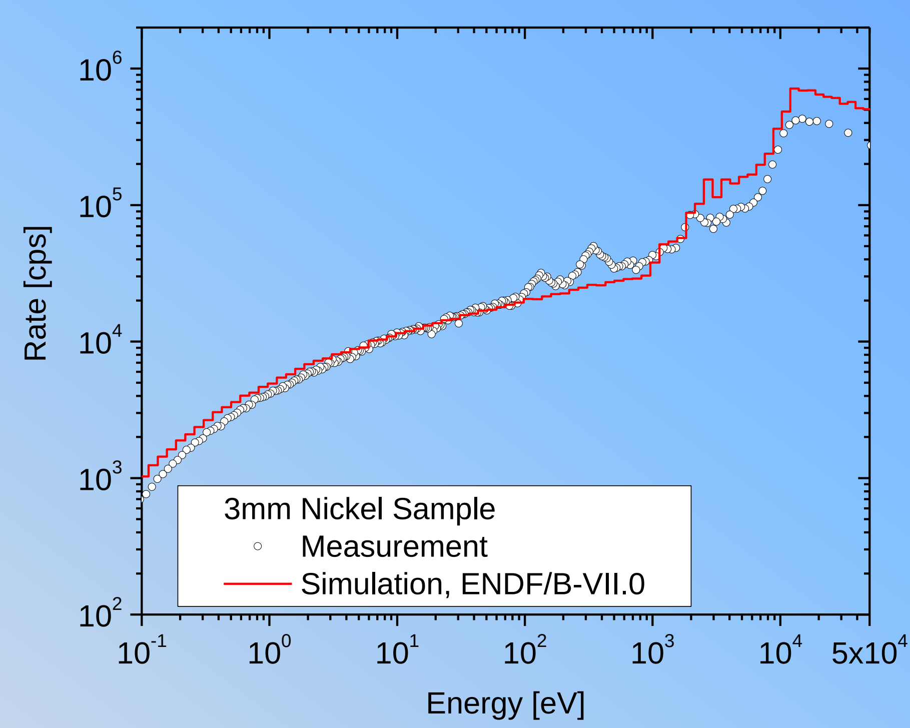
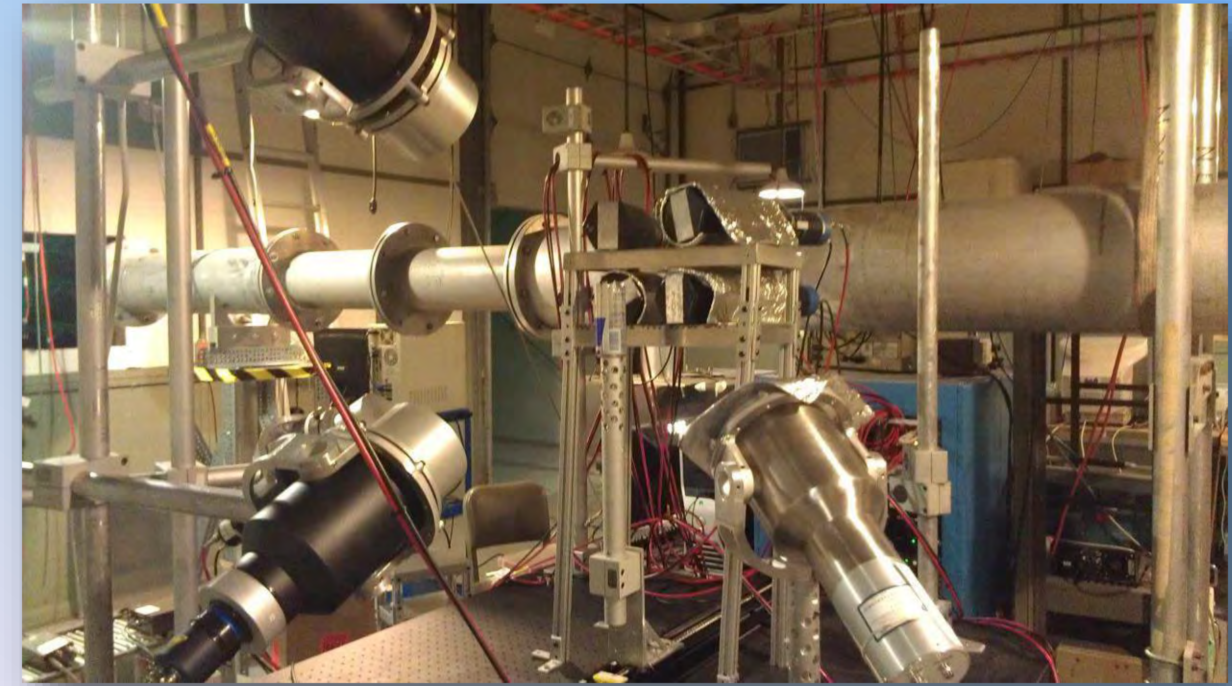
Ni Capture rate

- 2mm YAP detector, 3mm nickel sample
  - Low capture cross section → Low S/B
  - Reasonable agreement with ENDF/B-VII.1
  - Additional peaks observed near 200-300 eV → possible impurities in sample





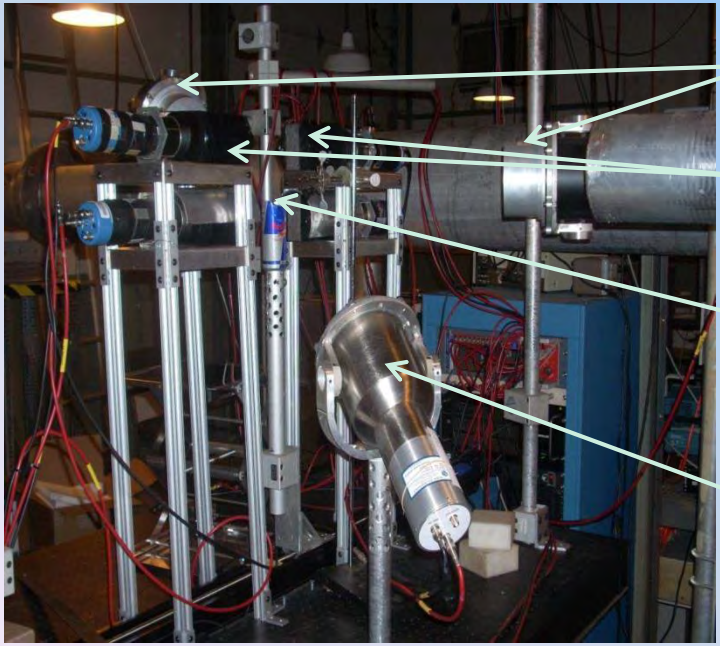
Prompt Fission Neutron spectra



Experimental Setup

- Neutron Detectors
  - EJ-204 Plastic Scintillator
    - 0.5” x 5”
    - 47 cm away from center of sample
  - 2 EJ-301 Liquid Scintillators
    - 3” x 5”
    - 50 cm away from center of sample

- Gamma Detectors
  - 4 BaF_2 detectors on loan from ORNL
  - Hexagonal detectors 2” x 5”
  - 10 cm from center of sample
  - ¼” lead shield between detectors
    - Reducing scattering between detectors



EJ-301 Detectors

Gamma Detectors

Sample Position

EJ-204 Detector

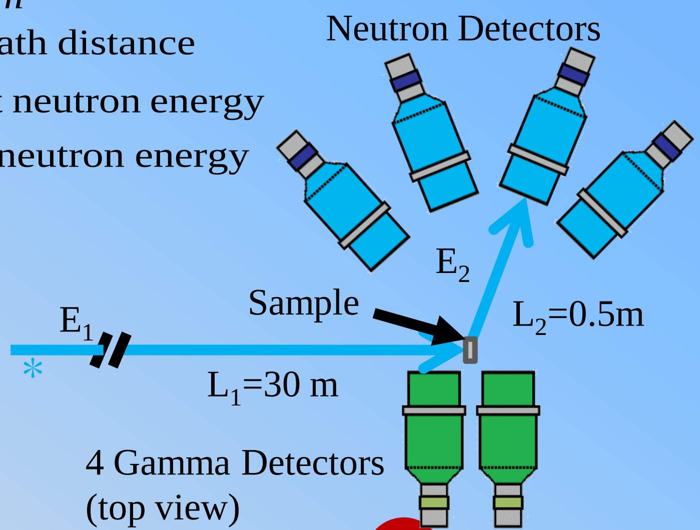
$$ToF = \frac{kL_1}{\sqrt{E_1}} + \frac{kL_2}{\sqrt{E_2}}$$

$$k \approx 72.3 \frac{\mu s \, eV^{1/2}}{m}$$

$L_{1,2}$ – flightpath distance

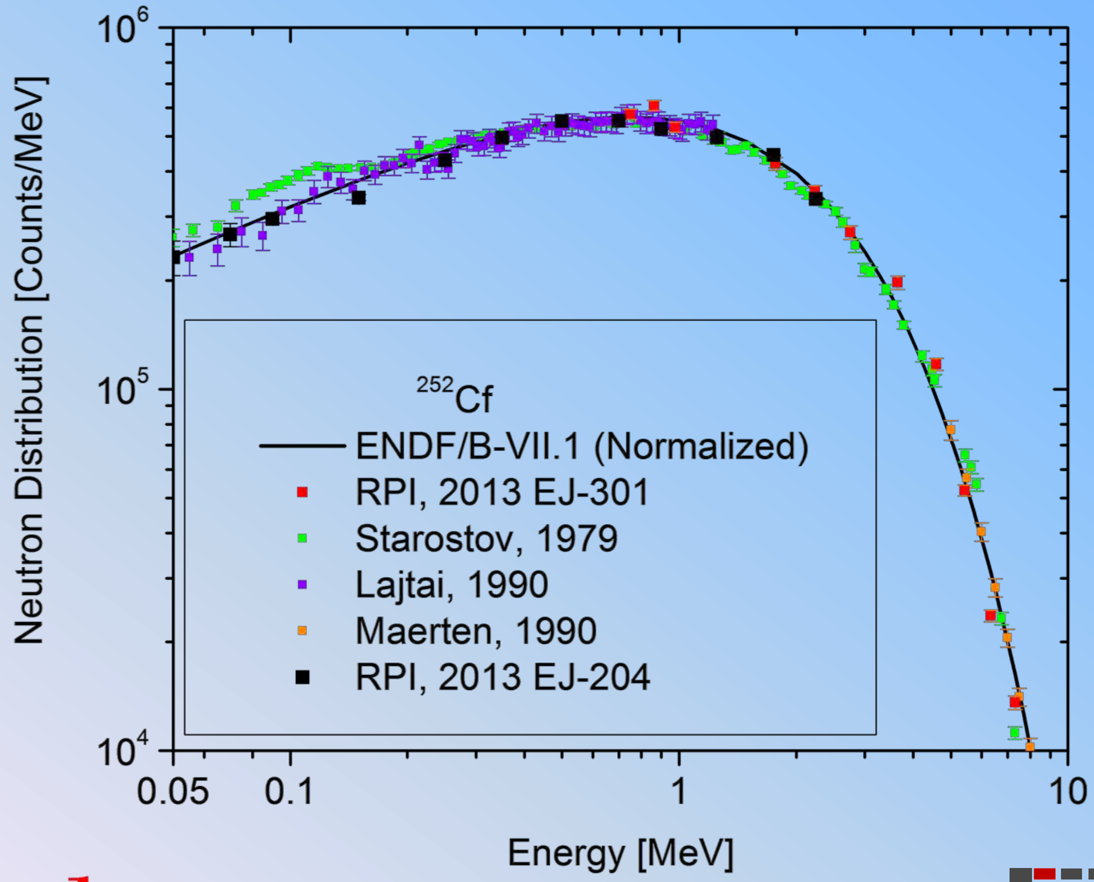
E_1 – incident neutron energy

E_2 – fission neutron energy



^{252}Cf Prompt Fission Neutron Spectrum

- Good agreement seen between the RPI datasets in the overlap region from 0.7 MeV to 2 MeV
- Combined datasets provide measurement from 0.05 Mev to 7 MeV



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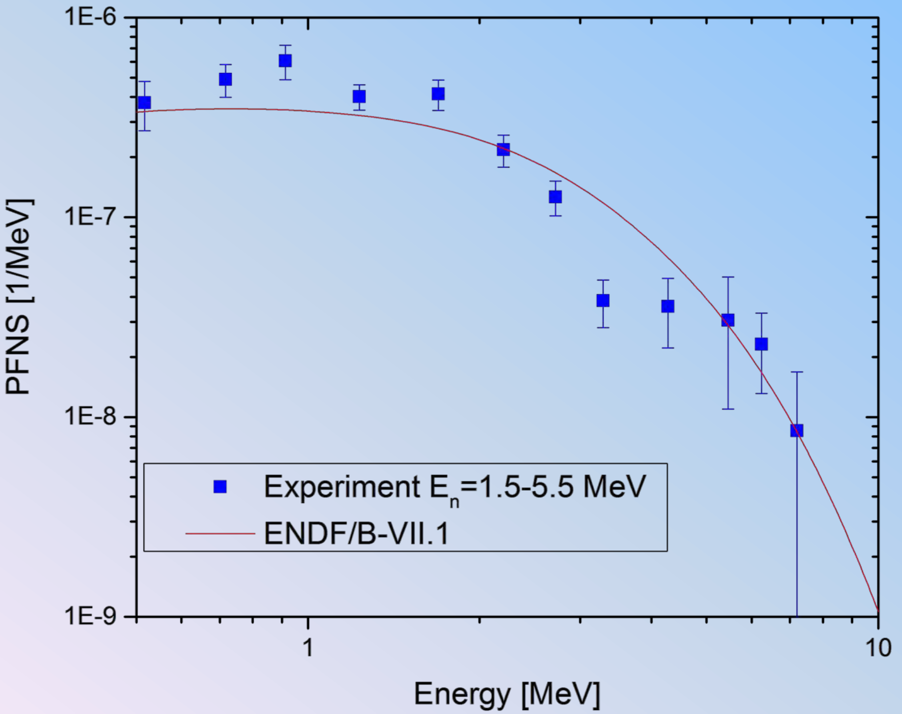
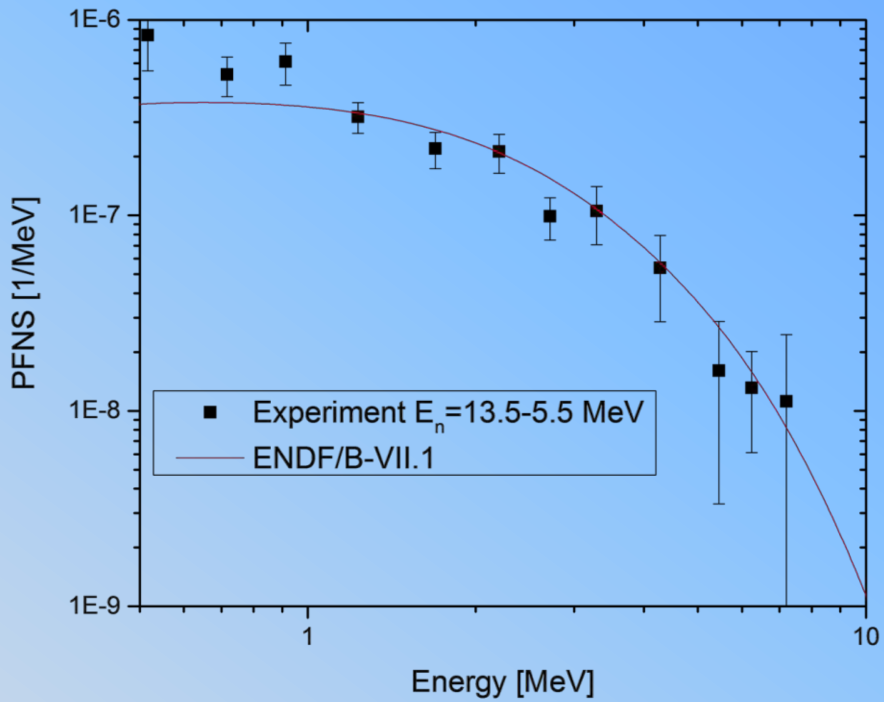
^{238}U Prompt Fission Neutron Spectrum

- Spectrum is integrated over two incident energy regions, first chance fission and second chance fission
- Data shows good agreement with current evaluations
- Increase near 1 MeV agrees with new data by Sardet *et. al.*
- Both spectra normalized at 2.25 MeV





LINAC 2020 Refurbishment and Upgrade Plan

- **Project aims at refurbishment and upgrade of the accelerator**
  - Increase neutron production as short pulses
    - Increase the electron beam energy
    - Modernize the electron beam control system
  - Provide longevity
    - Replace all major components and acquire spares

- **Funded by DOE-NR and NCSP through BMPC/KAPL**

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